THE JOURNAL

OF THE

AMERICAN CERAMIC SOCIETY

JULY 1, 1942

MONTHLY PUBLICATION DEVOTED TO THE ARTS AND SCIENCES RELATED TO THE SILICATE INDUSTRIES

TABLE OF CONTENTS

Vol. 25 July 1, 1942 No. 11

THE JOURNAL

Survey of Literature on Slag Tests for Refractory Materials..... 283–294

By T. L. Hurst and E. B. Read

Electric Furnace Study of the $MgO–SiO_2$ System..... 294–310

By R. R. Ralston and G. T. Faust

Refractories Service Conditions in the Blast Furnace..... 311–320

By Hobart M. Kraner

Influence of Fluxes of Spodumene and Feldspar Mixtures on Properties of Chinaware Bodies. 321–326

By H. G. Schurecht, J. K. Shapiro, and Z. Zabawsky

Publication Office: 20th & Northampton Sts., Easton, Pa.
Editorial Office: 2525 N. High St., Columbus, Ohio
Committee on Publications: D. E. Sharp, *Chairman;* E. E. Marbaker, J. B. Austin, G. H. Spencer-Strong, Ross C. Purdy.
Entered as second-class matter at the post office at Easton, Pa., under the act of March 3, 1879. Published monthly.
Subscription fifteen dollars ($15.00) a year. Single numbers $1.50
(*Foreign and Canadian postage, 50¢ additional on subscriptions*)
(*Copyright 1942, American Ceramic Society, Inc.*)

THE JOURNAL

OF

THE AMERICAN CERAMIC SOCIETY

Vol. 25 July 1, 1942 No. 11

SURVEY OF LITERATURE ON SLAG TESTS FOR REFRACTORY MATERIALS*

By T. L. Hurst and E. B. Read†

Abstract

A survey of the literature for the period 1932 through 1940 on the subject of slag tests for refractory materials is presented. This survey supplements similar reviews of Ferguson and of Simpson.

A classified index to methods of testing and means for evaluating slag attack on refractories is also presented. This key has been prepared from references which appear in the present survey and also in the two previous articles.

All of the references cited are to be found in the appended Bibliography.

I. Introduction

The literature on slag tests for refractory materials was reviewed thoroughly by Ferguson[48] in 1928 and by Simpson[151] in 1932. The present survey supplements the work of these authors and covers the material published during the period of 1932 through 1940. Slag tests and the methods used to measure the extent of slag attack have been classified and arranged in outline form. This outline was devised to facilitate reference to particular phases of the subject by providing key citations to the accompanying Bibliography.

II. Test Methods Designated as Type I

The tests included under this heading are characterized chiefly by relatively large quantities of refractory in contact with small amounts of slag. In almost all cases, moreover, the slag is placed on the refractory test specimen at room temperature, and the materials are heated together to the desired temperature. Such methods, which have certain advantages in carrying out tests for observing slag-refractory reactions, are widely used, and a large proportion of the recent studies have employed this principle.

The simplest test procedure consists of placing a pellet, cube, or cylinder molded from crushed slag on the surface of the refractory, after which the heat-treatment is given. Hyslop[80] heated a cylinder of dolomite slag on the surface of a test brick and measured the rate at which the slag was consumed. He considered this rate to be indicative of the chemical activity of the refractory and slag.

Hugill and Green,[84, 85] after definite heat-treatment, measured the extent of corrosion of the refractory and the depth of penetration of a slag cylinder. Chesters and Lynam[19] used the expanded volume and the bursting point of a test brick on which a pill of slag had been melted to determine the slag resistance of the refractory.

In addition to observing the depth of slag penetration, Chesters and Howie,[17] Chesters and Lee,[18] and Hugill and Green[83] measured the diameter of the pool of slag that was formed when a slag pill was melted on the surface of a test brick. Changes in the modulus of rupture of the brick after slagging were also reported by Chesters and his co-workers. Mellor and Green,[114] who favored cylindrically shaped slag samples, measured the extent of slag action by the depth of penetration of the slag into the refractory.

Schurecht[149] designed a test in which spheres of slag were placed on specially prepared refractory disks. The heights and diameters of the spheres were observed after firing, and their volumes were determined by optical projection methods. Schurecht states that cut sections are unsatisfactory to show slag penetration.

Several investigators have mentioned the skin effect of the refractory surface on slag penetration, and they point out that when cavities cut in the brick are filled with slag the conditions of the initial contact of slag and refractory are changed.

Dear[36] and Haff, Dear, and Whittemore[63] packed foundry ladle slag in wells drilled in the face of a $2^1/_2$-by 9-in. test brick. They also placed slag pills on the original surface of the same brick, which was supported at both ends during heating. The slag attack was measured by the sagging of the brick and the penetration of the slag.

Budnikov[16] bored holes in cubes cut from test brick,

* Received July 16, 1941.

† Industrial Fellows, Multiple Industrial Fellowship of the American Refractories Institute, Mellon Institute, Pittsburgh, Pa.

filled the holes with slag, and measured the slag penetration after heating. He also heated the samples by inserting carbon electrodes in the slag holes.[14] The fusion temperature of the slag and refractory was then determined, and this figure indicated the resistance of the refractory to slag attack.

Portland cement clinker attacks refractories to a measurable degree. Heuer[72] and Miehr[116] packed typical cement clinker in holes drilled in standard refractory shapes and observed the extent of the slag reaction.

Rochow[132] found that when slag was placed in a cavity in a test brick, the brick expanded and bloated during firing. He used the expanded volume as a measure of the slag attack.

Simpson[152] melted coal-ash slags in crucibles cut from the test brick. He noted the critical temperatures of the slag attack and gave an extensive report on the resistance of several refractories to various slags.

The German standard slag test[39] requires, in part, that slag attack be determined by heating the slag in crucibles cut from the refractory being tested. The resistance of the refractory to slag attack is indicated by the increase in the cross-sectional area of the crucible cavity after the test. Bartsch[7] criticized this test because no definite heating schedule is prescribed and also because changes in composition of the slag by solution of the crucible during the test are not considered.

Letort,[104] Schauer,[147] and Cross and Rees[34] also measured slag attack and penetration by the crucible method. Schauer modified the test by placing a pyramid of slag in the crucible cavity. The sinking of the pyramid during firing, its final height after testing, and the penetration of the slag in the bottom and sides of the crucible were observed.

As a substitute for crucibles cut out of the test brick, many investigators have used molded or cast crucibles. Chesters and Lee,[18] Letort,[104] Baudewyns,[8] and others[34, 147] have described experiments in which slag was melted in molded crucibles and the attack was observed by penetration measurements after cooling.

III. Test Methods Designated as Type II

Tests grouped under this classification may be termed immersion methods. They are characterized by relatively small quantities of refractories in contact with large quantities of corrosive fluids. The two basic variations are the immersion of the refractories in (1) slags or other corrosive liquids and (2) destructive gases or vapors. Under test conditions in which only one face or surface of the refractory is exposed to slag attack, as in a hearth or wall, the test specimen must be located below the slag level to distinguish tests of this type from the impingement method (section IV). The level of the liquid, moreover, must be reasonably constant and of considerable depth.

Sachs[135] designed a cylindrical pot-type furnace fitted with vertical slots in which bar-shaped test pieces were placed and exposed to slag attack. Changes in the volumes of the test bars were followed in recording the extent of the slag action. Baudewyns[8] employed pots made of the test refractory, in which large quantities of slags or glasses were melted. The slags were heated, cooled, and analyzed for composition changes; the slag penetration into the refractory pot was also observed.

Pole and Moore[126] suspended standard test brick lengthwise so that the ends were immersed to a depth of $2^1/_2$ in. in melted phosphate slag. Slag attack was determined by the loss in weight and volume of the brick. These writers report that porosity is an important factor because high porosity increases the slag reaction in relation to the chemical composition of the brick. Petrographic studies made by these authors indicate that complex pyrochemical reactions take place during the immersion period.

By using an electric furnace to heat silica brick that had been immersed in a bath of slag, Starostin[154] observed the action of the slag and measured the final volume of the test sample. He concludes that slag resistance is largely a function of the porosity of the refractory.

Test pieces in the form of prisms were exposed to slag action in an electric furnace by Endell and Wens,[42] who conclude that slag attack increases with decreasing slag viscosity and is almost independent of the melted composition. Hartmann[64] also immersed prisms of refractory material in molten alkalis in an electric furnace. He correlated the slag attack with slag fluidity, and he states that the chemical compositions of some refractories influence their resistance to certain corrosive salts.

Bartsch[6] subjected small blocks of refractory to the action of molten sodium salts in both platinum and fireclay crucibles. The results were difficult to interpret because the larger grains of the refractory loosened during the test.

Results which agree well with service tests were obtained by Turner,[162] who exposed crushed refractory to melts of sodium and potassium carbonates. Mellor and Green[114] analyzed the melt, which was obtained by saturating a molten slag with the test refractory. They believe that the composition, together with the total amount of refractory necessary to saturate the slag at various temperatures, is an important factor governing the reactions between slags and refractories. Jebsen-Marwedel[96] dissolved various kinds and amounts of refractories in different slags, and equal quantities of each liquid were cooled freely so as to form buttons or drops. The diameters of these drops were measured and used as an index of the comparative surface tensions of the melts.

Intensive studies have been made during the past few years on the destructive effects of gases and corrosive vapors on refractories. Because the action of gases and vapors is less apparent than that of most slags, their influence is seldom noticed until the refractories have been subjected to extensive damage.

Clews, Green, and their associates* have conducted extensive investigations on the slagging action of alkali vapors on refractories. Their procedures, in general, consisted of exposing samples of refractories to different

* References 20 to 30, inclusive.

vapors under controlled conditions of time and temperature. The refractory samples were then inspected for discoloration, cracking, erosion, and changes in weight, dimensions, and modulus of rupture. The most important vapors whose action on refractories was studied included those of soda and potash (or a potash-silica glass), sodium and potassium chlorides, sodium carbonate, and sodium aluminate, as well as steam and carbon monoxide.

Actual service tests have been used by many investigators* to obtain definite results that could not be reliably determined by accelerated laboratory methods.

So many variable factors must be considered in selecting refractories for use in atmospheres which contain destructive vapors that actual service tests were recommended by Fabianic,[45] Rochow and McDowell,[133] and Donoho.[39] These investigators placed refractories in particular installations to expose them to the gases for considerable periods of time. Comparisons were made of the different refractories after exposure and their relative resistance to attack was noted.

IV. Test Methods Designated as Type III

The type III test methods involve the impingement of slag against the hot refractory test specimens. Such test methods are claimed to simulate actual conditions. The chief criticism of these procedures is the accelerated reactions that are necessary for laboratory studies. The principal differences in these test methods are (1) the shape and features of the furnace and (2) the means of admitting the slag into the test chamber. Many investigators have preferred to build a panel of test brick inside a larger furnace, whereas others have constructed the inside walls of the test furnace entirely of the refractory being studied. The means by which the slag is admitted depends mainly on the design of the test furnace.

Hugill and Green[83, 84, 85] injected powdered slag into a flame that impinged against the test brick at an angle of 45 degrees. The extent of erosion indicated the slag resistance of the refractory. Great difficulty was encountered, however, to obtain quantitative measurements on the extent of the erosion. Their observations were classified as follows: (*a*) the depth of the surface layer removed by erosion, (*b*) the area of erosion that appeared on the exposed refractory surface, (*c*) the channeling of the brick caused by the slag flow, (*d*) the widening of any cracks that resulted from the solution of the refractory, and (*e*) the destruction of the joints between the brick by the slag.

The attack of fuel-oil ash on refractories was investigated by Faulkner,[46] who built a panel of test brick, inclined at an angle of 20 degrees from the vertical, in front of the bag walls of a furnace. Definite amounts of slag were blown at intervals against the panel over a 20-hour period, and the degree of attack was noted after cooling. Wilson[166] placed test brick inside an oil-fired furnace and directed powdered slag under air pressure horizontally against them.

The alternate German quality standard[59] prescribes a suitable electric furnace equipped with a removable tube in which the test sample is placed. The test is conducted by cutting and smoothing small cylinders from the refractory, heating them individually in an electric furnace, and sprinkling powdered slag on their surfaces for 15 minutes under controlled conditions. The slag is allowed to drain from the specimen for 15 minutes after the final injection. By weighing and determining the volume before and after slagging, the percentage weight and volume changes of the test body are calculated. The test cylinder is then cut along its long axis, and the slag penetration is measured for the entire length.

Hyslop[90] ascertained the amount of slag that was needed to erode or cut through a bar-shaped sample of refractory. Dodd,[37] however, states that although this test is fairly comparative it is not satisfactory because the specimen is heated from all four sides and therefore fails to simulate service conditions.

Several types of furnaces have been designed in which the test brick formed the inside walls. Hursh[87] used a gas-fired cylindrical furnace that was revolved while the flame and slag were directed downward from a stationary port so as to strike the walls at an angle of approximately 45 degrees. He also designed a stationary furnace equipped with a rotating port mounted above it through which the slag and flame were admitted downward and into the chamber. This new furnace was preferred because it enabled temperature-gradient measurements to be made through its walls. These temperature gradients, under operating conditions, were found to agree with those observed in industrial boiler furnaces. After their exposure to the slag, the brick were compared to determine their relative slag resistance, and the depth of erosion was measured.

With the rotating and stationary furnaces, the test brick could not be observed until the furnace had been cooled, and the inside lining had to be dismantled before the specimens could be removed. Hursh and Welliver[88] improved the furnace design in an attempt to correlate the slagging action more closely with the furnace temperature and the slag viscosity. They built several ports through the furnace walls in which whole brick were placed so that they were exposed to the slag and could also be easily withdrawn at any time. This procedure enabled the slag action to be observed through a range of temperatures and slag viscosities during one continuous run of the furnace.

Fettke and Stewart[50] and Stewart,[155] who studied the slagging action of several western Pennsylvania coals on various refractories, used a cylindrical, downdraft furnace that was fired from above with pulverized coal which provided its own slag. Vickers and Bell[163] also used a cylindrical furnace lined with the test brick. A rotating burner entered at the top of the furnace, and the slag was injected with the fuel.

A commercial laboratory slag furnace that has given satisfactory results is a cylindrical updraft unit with two fixed burners for introducing the fuel. Powdered slag is charged by compressed air through a rotating pipe at the top of the furnace, and the excess slag is collected in a basin below the burner level.[56]

* See references 19, 36, 62, 71, 97, 99.

An oil-fired furnace of rectangular type was designed by Patterson[124] for slag tests. Coal with low-fusion ash was pulverized and mixed with fuel oil, and this mixture was burned so that the flame impinged on one test panel. Another panel of the same refractory was exposed only to an oil flame. The two test panels were cooled and compared. The differences in degree of attack were attributed to the action of the coal.

Litinsky[105] built a panel of test brick in one side of a rectangular furnace and directed a flame against it at an angle of 45 degrees. Slag blown into the furnace from the top was carried by the flame against the test panel, and the erosion and penetration of the slag into the refractories were observed. Mellor and Green[114] set test brick in the wall of a furnace and directed definite amounts of slag against them at an angle of 45 degrees. Petrographic analyses were made of the refractories after testing, in addition to the usual examinations and penetration measurements.

Norton[120] admitted slag from above the test piece and allowed it to drip on the refractory. He states that the results obtained by this test conform closely to service reactions.

McMullen[109] has recently described a slag-test furnace that is electrically heated and operated at 1600°C. The gases are admitted to the chamber so as to produce any desired atmospheric conditions. The slag is introduced in the form of rods made by rolling the crushed slag into tubes of waxed paper. Small amounts of a binding agent are used to strengthen these rods. The slag is admitted at a uniform rate; after it melts, it flows across the test specimen, which has been inclined at an angle of 30 degrees. The spent slag is collected in a sand trap and can be easily removed. The degree of erosion is determined by measuring the depth of the trough which the slag has made in the refractory. Penetration measurements are also made on the sample by cutting it through the slagged area.

Because of the exceedingly variable nature of slag action and the short times and accelerated reactions encountered in laboratory testing, actual service tests are conducted extensively. Reports of these tests concern both service conditions and comparison between service and laboratory reactions. Kraner[103] has discussed the slagging of refractories in the steel industry. Bailey,[4] Kollbohn,[102] and Rammler,[128] have reviewed boiler-furnace slagging difficulties and the design of more slag-resistant units. Chesters and Lynam[19] have compared the results obtained with different refractories in open-hearth service. Donoho[30] observed the life of various test refractories placed just above the taphole in a cupola lining, and from the results he has been able to select the best refractory for that particular service. Pouring nozzles and steel-pouring refractories have been ably discussed by Kinney[99] and by Dodd and Green.[28]

Although no definite conclusions can be reached because of the diversity of opinions concerning the properties needed by such refractories, the fact that the composition and texture must be considered separately is generally accepted. In other words, the composition must be such that it offers chemical resistance to the slag, and the physical properties are then adjusted to reduce slag penetration and corrosion to a minimum.

V. Cone-Fusion and Miscellaneous Test Methods Designated as Type IV

The cone-fusion test is one of the simplest methods employed to determine the effect of different slags and slag mixtures on the softening and fusion temperatures of refractories. The intimate mixing of various quantities of slag with refractories in order to form cones is no definite simulant of actual service. It is useful, however, in studying the behavior of brick and slag under conditions that favor extensive chemical reaction. The refractory properties of the mixtures as well as the reaction products can be determined.

Chesters and Lee[18] examined cone fusions petrographically, as did Heuer,[73] Hugill,[84] and others. These investigators correlated the mineral phases and compounds with the equilibrium diagrams of the major constituents. Budnikov[16] studied the effect of sodium sulfide, sodium sulfate, and powdered coal on refractories and made petrographic studies of the fused cones.

Hugill and Green[84, 85] compared cone-fusion tests with the slag penetration obtained by the melted-pellet and impingement methods. The cone tests revealed the relatively low temperatures at which the first liquid formed. These temperatures were confined to a narrow range despite a wide variation in the compositions of the slags and refractories. Emphasis was placed on this eutectic because it was believed to represent the earliest stage of slag attack.

The interval between the softening and flattening of cones made of slag-refractory mixtures indicates the critical range of deformation of refractories in contact with these slags according to Dodd.[27] Mellor and Green[114] believed that the reactivity between slag and refractory and the properties of the slag-refractory product were of fundamental importance in studies of slag attack.

Cone-fusion tests are satisfactory to determine many basic principles inasmuch as the factors of chemical reaction, intimacy of contact, refractoriness, viscosity, crystallization, and atmospheric conditions are involved.

Schauer[147] combined a cone-fusion test with a crucible-penetration test in a simple procedure which showed both the softening of the slag and its penetration into the refractory crucible. Fusions of both chips and cones of slag have been carried out by many investigators to evaluate the activity of the slag from its softening range.* Extensive work[40, 47, 95] has been done on the total solubility of refractories in slags and this work (see section VI (4)).

By mathematical treatment, Endell, Fehling, and Kley[41] and Fehling[47] correlated the flow of viscous oils over test panels with the flow of slags over refractories at elevated temperatures. They have concluded that erosion and flow are functions of the viscosity of the slag and of the solubility of the refractory in the slag

* See references 18, 43, 51, 114, 136, 147.

and that they are almost independent of combustion conditions.

VI. Measurement of Slag Attack

The various methods have been reviewed by which reactions between slag and refractories have been produced, and a summary is presented of the methods by which the resulting reactions have been evaluated. Recent techniques are especially noteworthy, although most of these procedures will only be mentioned.

(1) Chemical Analysis

Complete analyses have been made of the slag and refractory, both before and after testing. It has been found, however, that the labor and time involved, the large errors arising in sampling, and the limited application of the data obtained make chemical analyses unsatisfactory in most cases.[37, 139] Analysis of specific oxides and comparison of oxide ratios before and after testing have been advocated by some investigators. They believe that such analyses are useful to indicate the reactions and changes that accompany slagging.*

Clews, Green, and associates† analyzed the alkalis that were absorbed by refractories after exposure to and impregnation with corrosive vapors. By this method, these investigators determined the absorption of the test specimens, the amount of alkali retained by them, and the rate of volatilization of the absorbed matter. These data were then correlated with the service life of refractories in contact with such vapors. After having exposed the refractories to the action of typical vapors, they also determined the solubility of the test specimens in dilute HCl. The extent of solution was of the same order as the chemical decomposition produced by the vapors.

Chemical methods were employed by Bartsch[6] in his effort to determine the effect of fused salts on refractories. Turner[152] measured the chemical resistance of refractories by analyzing the product obtained from their reactions with sodium and potassium carbonates.

Although analyses of slags and refractories provide data that may be used advantageously to evaluate slag reactions on refractory materials, they are insufficient to indicate slag attack without additional information.

(2) Physical Measurements

The usual methods employed to determine the extent of slag attack on refractories include volume changes, linear erosion, porosity measurements, weight changes, and modulus of rupture tests. These well-known procedures have been used in almost all slag studies. Visual comparisons between various kinds of brick after exposure to slags are made to indicate the best refractory under particular service conditions.

The determination of the extent and depth of the slag penetration into the refractory requires careful observation and measurement. After being exposed to slag action, the test samples are cut open and measurements of the areas of penetration are made planimetrically. Macroscopic and low-power microscopic examinations are usually satisfactory to locate the deepest slag penetration.

Schurecht[149] has described the optical projection methods which he used to find the slump and final volume of a slag sphere after it had been heated on the refractory. The difference in the shape and volume of the original and the final slag sample served as an index of the attack of the slag on the refractory. The angle of contact between the melted slag button and the refractory, although difficult to measure, corresponded well with the wetting ability and slag action as determined by the slump and volume tests.

Schauer[147] also has measured the slump of slag cones as well as the penetration of the slag into the refractory. Hyslop's[90] method was similar; he measured the rate at which a standard cylinder of slag was consumed by the test refractory at definite temperatures.

The evaluation of slag action by determining the pyrometric cone equivalent of the slag and slag-refractory mixtures involves well-known methods of measurement.

(3) Petrographic Analysis

Microscopic studies have been reported by investigators of slag action on refractory materials.‡ Not only are the structural characteristics and particle sizes of the refractories brought out but the solution, crystallization, and the phase relationships of the slag-refractory reactions are determined by petrographic analyses. The procedures are specialized and, as in the case of chemical analyses, require the services of experienced technicians.

(4) Miscellaneous Methods

Further advances in the measurement of slag attack have been made by fundamental studies of the viscosities and surface tensions of molten slags and the determination of the critical temperatures at which drops are formed. Slag viscosities and surface tensions as well as changes in densities have been closely associated with slag attack by Endell and others.§ These determinations, however, are not easily performed as they necessitate both appropriate equipment and technique of operation.[76]

Reagan[129] and Herty[70] have described a simple viscosimeter for control purposes. It consists of a horizontal steel tube with a spout mounted vertically at one end. Slag is poured into the spout, and the distance it travels in the tube indicates its viscosity. Other methods for studying the flow characteristics of slags have been devised. Barrett[5] cast slag billets from a special furnace designed to insure uniform slag composition. These slag billets were heated on a refractory slab, and their rate of deformation or slumping was observed.

Total solubility of the refractory in the slag has been correlated with slag resistance by several writers. Jebsen-Marwedel[96] associated solubility with the surface tension and viscosity of the slag-refractory liquid. He has demonstrated that definite relationships exist between the surface tensions and the diameters of

* See references 19, 41, 66, 68, 121, 137, 139.
† References 20 to 30, inclusive.
‡ See references 37, 41, 43, 47, 51, 66, 84, 97, 121, 136.
§ See references 5, 37, 41, 43, 47, 51, 66, 84, 97, 121, 136.

drops formed by molten slag in which varying amounts of refractory had been dissolved. Direct measurements of the diameters of these drops served, therefore, as a simple method for determining the surface tension of the liquids.

Many investigators of slag attack, particularly those specialists concerned with fundamental physicochemical studies, have emphasized that each slag action is an individual problem and that many procedures and measurements must be employed to express the results.

VII. Discussion

Rees[130] has expressed four factors on which slagging depends; these include (1) the rate of reaction between the slag and the refractory materials, (2) the rate of removal of the reaction products, (3) the rate of delivery of fresh slag against the refractory, and (4) the characteristics of the refractory, such as composition, porosity and structure, grain size, density, and associated properties. These factors are similar to those suggested by Mellor, Dodd, Green, and others.*

Kraner[103] emphasized the importance of care in controlling experimental conditions. Some of the most important factors that require special attention are (1) the maintenance of the temperature or temperature cycle so as to insure the uniform application of heat to all test pieces, (2) atmospheric uniformity, (3) proper slag composition, and (4) viscosity of the slag during the test.

Mellor[114] divided slag attack into the corrosive or chemically vicious type and the erosive or attrition type. Baudewyns[8] has made the same distinctions. He classes the corrosive action into stages of (1) capillary penetration, especially aided by capillary attraction, and (2) the resulting chemical attack. He states that porosity is the most important factor, and his observations of zones of erosion in the refractory material are similar to those reported by Heuer.[73]

Hugill and Green[84] believe that all slag attacks are similar in the early stages and are associated with the formation of the first liquid or eutectic between the slag and refractory. Mechanical abrasion is important in the initial phases of impingement tests. After the refractory surface has been roughened by the slag, additional slag particles lodge and melt in the cavities and crevices that are formed. The melted slag flows down the surface and penetrates the brick, and the attack becomes one of corrosion, penetration, and solution.

Petrographic studies have revealed, in general, that various crystalline and vitreous products are formed in accordance with the time and temperature of the reaction and the composition of the slag and refractory. Zones or bands that are loci for particular mineral and glassy phases usually have been observed. These zones, which are roughly parallel to the exposed face of the brick in most cases, have been developed from the hot toward the cold end.†

Petrographic data have led to pyrochemical studies of the equilibria between slags and refractories. By the findings, the solubilities and reactivities of the slags as well as the mineralogical changes that result from slag attack have been more easily understood. Phase diagrams have been constructed to illustrate the systems and to aid in predicting the extent of the slag reaction with refractories.‡

More recent advances in the problem of evaluating slag attack on refractory materials have involved studies of the viscosities and surface tensions of the slags and the effects of these properties on slag action.

Endell, Fehling, and Kley[41] and Fehling[47] have outined a general theory of the dynamics of erosion developing equations to calculate the extent of erosion. The most important factors involved in this work are solution and diffusion. Solution is computed by means of phase diagrams, but diffusion is difficult to evaluate.

Endell‡ has pointed out that solubility of refractories in slags is difficult to define, and in reality it is used to express a sum of changes for which no other designation exists. Such a situation, he believes, is especially true if only the end state is recognized and the middle states or intermediate conditions are eliminated.

Endell, Fehling, and Kley[41] have found that an increased fluidity of the slag increases its destructive action. The velocity of flow and the thickness of a film of slag on a refractory surface depend more on the fluidity of the slag than on the angle of inclination of the path of flow. From these findings, mathematical expressions have been formulated to calculate the attack of slags on refractory surfaces. Their conclusions agree with those of Hartmann,[67] who has reported that fluidity is the principal factor governing slag corrosion, whereas slag density is an associated factor because it also varies with the temperature. Chemical composition, especially in the case of alkali silicates, influences the slag fluidity.

Another interesting conclusion reached by these investigators is that higher solubilities of refractories in slags are not important from the standpoint of the amount of refractory necessary to saturate the slag. Its real importance is associated with the increase in the concentration gradient and the resulting acceleration of the diffusion of the refractory through the slag.

Flow studies have also shown that the range between the softening of the slag and the formation of drops is usually very narrow. At temperatures above the critical point of drop formation, the destructive action of the slag is greatly increased.

Considering future work in the study of slag attack on refractories, Mellor and Green[114] believe that the fundamental approach should include (1) studies of the reactivity of slags and refractories, (2) complete knowledge of the properties of the original slag and the slag-refractory product, and (3) analysis of the penetration of the refractory by the slag.

Dodd[37] has found that the chief difficulties encountered in laboratory tests include the complete reproduction of service conditions or the elimination of all but the one factor that is being observed and the quantitative measurements of the results obtained. He

* See references 37, 38, 83, 84, 85, 114, 139.

† See references 37, 41, 43, 47, 51, 66, 84, 97, 121, 136.

‡ See references 40, 43, 47, 136.

thinks that future work should be concentrated on fundamental chemical and physical effects.

Fehling,[41] Endell,[43] and co-workers[136] agree with these ideas and recommend studies on (1) slag viscosity versus composition and temperature, (2) solubility of the refractory in the slag, (3) diffusion of the refractory in the slag, and (4) measurement of erosion under strictly defined conditions.

Kraner's[103] summary of the requirements for slag testing are similar. He proposes different tests for slagging actions that occur in different services, with definitely controlled conditions which include temperature, treatment of test samples, atmosphere, slag composition, viscosity, rate of slag application and drain, and rate of flow of combustion gases over the refractories being tested.

REFERENCE TABLE TO SLAG-TEST METHODS: I–II*

I, Subject Matter Arranged According to Nature of Method Employed

Type I: Slag Placed on Refractory Test Specimen Before Heating

(*A*) *Slag Placed on Original Surface of Test Brick*

(1) Slag pellets, blocks, or cylinders placed on surface of brick: 17, 18, 19, 36, 62, 83, 84, 85, 90, 131, 156.

(2) Slag packed in retaining rings on brick surface (old A.S.T.M. test): 1, 2, 3, 32, 57, 61, 75, 80, 98, 125.

(3) Slag sandwiched between whole brick: 13.

(4) Slag placed on refractory disks: 149.

(*B*) *Slag Placed in Retaining Cavity in Refractory Test Specimens*

(1) Slag packed in holes drilled in test brick: 2, 16, 36, 62, 72, 119, 132.

(2) Slag packed in crucibles cut out of brick: 7, 16, 59, 104, 147, 152.

(3) Slag packed in molded refractory crucibles: 18, 52, 100, 107, 142, 147.

(4) Slag packed in molded hollow brick: 74, 160.

(5) Slag placed in trough cut in sloping end of brick: 127.

Type II: Refractory Immersed in Corrosive Fluid

(*A*) *Refractory Immersed in Molten Slag or Corrosive Fluid*

(1) Only one face of refractory exposed to slag.

(*a*) Refractory located beneath level of bath of slag or liquid: (i) bar- or rod-shaped refractory specimens: 138; (ii) open-hearth test furnace with constant slag depth: 148; (iii) large refractory crucibles or pots containing molten slag: 8, 44; (iv) full-size refractories in actual service: 8, 19, 36, 62, 71, 97, 99.

(*b*) Refractory located above slag or liquid level: (i) see type III, Impingement of Slag on Refractory.

(2) Many faces or surfaces of refractory exposed to slag.

(*a*) Rods immersed in molten slag: (i) stationary rods: 31, 135; (ii) rotating rods: 134;

(*b*) Brick immersed in molten slag: (i) brick simply immersed in slag: 6, 40, 41, 47, 96, 114; (ii) refractory suspended or partially immersed in slag: 126, 154; (iii) brick alternately dipped into and withdrawn from slag bath: 120; (iv) refractory completely dissolved in slag: 96, 114.

(*c*) Refractories immersed in certain corrosive chemicals and melts: (i) samples suspended in molten salts: 6, 41; (ii) crushed refractory immersed in molten salts: 53, 162; (iii) refractory immersed in concentrated acid or alkali: 11, 115, 123.

(*B*) *Refractory Immersed in Destructive Gases or Vapors*

(1) Samples exposed to salt vapors: 20–30, 161, 164.

(2) Brick impregnated with chemicals: 26, 30.

(3) Brick exposed to gases and vapors in service tests: 9, 10, 45, 133.

(4) Variables that affect the reactions between refractories and vapors: 26, 30, 41.

Type III: Impingement of Slag Against Refractory Test Specimens

(*A*) *Refractory Test Specimens Set Inside a Larger Furnace*

(1) Slag admitted from above, test brick set on furnace hearth.

(*a*) Slag fed with the flame: 85, 113, 120.

(*b*) Slag admitted independent of the flame: 55, 58, 109, 145.

(*c*) Melted slag allowed to flow over test brick: 6, 40, 43, 47, 109, 120, 136.

(2) Slag directed sidewise against panel of test brick.

(*a*) Slag fed with the flame: 83, 85, 146.

(*b*) Slag admitted separately: 46, 83, 85, 166.

(3) Slag directed against refractories heated in an electric furnace.

(*a*) Slag sprinkled over test rod: (i) rod rotated: 91; (ii) rod stationary (German Standard): 59.

(*b*) Slag impinged against test cubes: 65, 96.

(*c*) Slag allowed to flow across specimens: 109.

(*B*) *Refractory Test Specimens Form Walls of Furnace*

(1) Cylindrically shaped test furnace.

(*a*) Slag admitted with flame from above: (i) rotating furnace, fixed burner: 86, 87, 122; (ii) stationary furnace, rotating burner: Furnace dismantled to observe slag action: 37, 87, 163; draw trials removable at any time: 88.

(*b*) Slag delivered separately through rotating feed from above, fixed burners: 56.

(*c*) Slag provided by fuel, powdered coal: 50, 155.

(2) Square or rectangular test furnace.

(*a*) Premelted slag admitted from above against four walls of furnace: 63.

(*b*) Slag directed with flame against test wall: 85, 102, 105, 114, 124, 128, 158.

(*c*) Actual test in service: 4, 19, 39, 102, 103, 128.

Type IV: Miscellaneous Tests on Slags, Refractories, and Mixtures of Both

(*A*) *Cone Fusion Tests*

(1) P.C.E. and softening range of slags: 9, 10, 12, 16, 18, 43, 48, 54, 57, 60, 63, 72, 73, 74, 77, 82, 94, 101, 107, 112, 127, 136, 147, 148, 157, 165.

(2) P.C.E. of refractory-slag mixtures: 9, 10, 12, 18, 37, 43, 48, 54, 57, 60, 73, 77, 82, 85, 94, 101, 107, 112, 114, 118, 136, 157, 165.

(*B*) *Solubility Studies*

(1) Total solubility of refractory in slag: 6, 40, 41, 47, 96, 114, 139.

(2) Correlation with equilibrium diagrams: 37, 41, 47, 97, 121, 159.

(*C*) *Various Properties of the Slag and Slag-Refractory Mixtures*

(1) Viscosity determinations: 5, 37, 41, 43, 47, 51, 66, 84, 97, 121, 129, 136, 137.

(2) Surface-tension determinations: 5, 37, 41, 43, 47, 51, 66, 84, 96, 97, 121, 136, 139, 149.

(3) Formation of and size of drops: 38, 40, 41, 43, 47, 121, 136, 139.

(*D*) *Various Properties of the Refractory*

(1) Porosity determinations: 18, 78, 81, 92, 106, 119.

(2) Particle-size measurements: 19, 37, 93.

---

* Numbers in Reference Table are cited in the Bibliography section.

In Part II, p. 290, the same methods for measuring slag attack were used by many investigators; Bibliography citations, therefore, refer only to articles that describe either representative or original methods.

II, Subject Matter Arranged According to Methods Used to Evaluate Extent of Slag Attack*

Type I: Chemical Analyses

(*A*) *Original vs. Final Analyses*
(1) Complete chemical analyses: 139, 164.
(2) Analyses of certain oxides: 35, 40, 43, 52, 66, 68, 89, 107, 136, 139.
(3) Fuel-ash analysis vs. analysis of flue-dust slag: 112.
(*B*) *Volatilization of Vapors Absorbed by the Refractory:* 23, 24, 28, 29.
(*C*) *Solubility of Refractories in Certain Reagents:* 74, 98, 120.

Type II: Correlation of Physical Properties of Refractory and Slag with Slag Action

(*A*) *Comparison of Refractory Before and After Testing*
(1) Volume expansion: 18, 21, 23, 26, 41, 132.
(2) Volume loss: 65, 87, 119, 126, 138, 149.
(*a*) Inches of erosion of sample: 50, 134, 155, 158.
(*b*) Volume lost per unit area exposed to slag: 50, 86, 87, 155.
(*c*) Time necessary to destroy refractory rod by erosion: 37, 91.
(3) Porosity changes: 18, 19, 33, 40, 60, 81.
(4) Weight changes: 11, 26, 30, 119, 126, 164.
(5) Modulus of rupture: 18, 26, 30.
(*B*) *Physical Properties of Slag Alone*
(1) Surface tension and viscosity: 5, 38, 40, 51, 66, 96, 118, 129.
(2) Determination of critical temperature of slag.
(*a*) Formation of drops: 40, 43, 47, 51, 96, 121, 136.
(*b*) Softening range: 5, 17, 40, 43, 66, 76, 136.

Type III: Penetration of Slag Into Refractory

(*A*) *Macroscopic Measurements*
(1) Rate of complete absorption of slag by refractory: 90, 130.
(2) Areal and depth measurements of slag pool: 19, 85, 119, 134, 147, 149.
(3) Comparison of various refractories after testing: 45, 85, 87, 99, 115, 145.
(*B*) *Microscopic Measurements*
(1) Particles sizes and structural characteristics: 17, 19, 26, 30, 38, 84.
(2) Petrographic analysis: 19, 83, 84, 95, 108, 110, 111, 152, 160.

Type IV: Pyrochemical Studies

(*A*) *Solubility of Refractory in Slags:* 40, 41, 43, 47, 96, 114, 116, 136.
(*B*) *Equilibria Relationships Between Slag Constituents and Refractory:* 37, 41, 43, 47, 51, 66, 84, 97, 121, 136, 159.
(*C*) *Reactivity, Acidic or Basic:* 26, 30, 38, 117, 140, 144.
(*D*) *Cone Fusion Measurements:* 9, 10, 12, 16, 18, 48, 54, 57, 60, 72, 73, 77, 82, 94, 101, 107, 112, 147, 157, 165.

Bibliography

1. American Society for Testing Materials, "Report of Committee C-8 on Refractories," *Proc. A.S.T.M.*, **25** [Part I] 190–91 (1925).
2. American Society for Testing Materials, "Tentative Test for Slagging Action of Refractory Materials, C17–17T," *ibid.*, **17** [Part I] 669–70 (1917).
3. American Society for Testing Materials, "Tentative Test for Slagging Action of Refractory Materials," *ibid.*, **19** [Part I] 586–89 (1919).
4. E. G. Bailey, "Action of Slag from Fuel in Boiler Furnaces," *Bull. Amer. Ceram. Soc.*, **17** [2] 55–67 (1938).
5. E. P. Barrett and J. A. Taylor, "New Method for Studying Flow Characteristics of Glasses and Slags at Elevated Temperatures," *Jour. Amer. Ceram. Soc.*, **19** [2] 39–44 (1936).
6. Otto Bartsch, "Action of Sodium Sulfate on Refractory Materials," *Glastech. Ber.*, **11** [8] 285–93 (1933); *Ceram. Abs.*, **14** [4] 94 (1935).
7. Otto Bartsch, "Determination of Slag Attack by the Crucible Method," *Ber. deut. keram. Ges.*, **19** [10] 413–26 (1938); *Ceram. Abs.*, **18** [8] 212 (1939).
8. J. Baudewyns, "Attack of Refractory Materials Used in Glassmaking," *Ing. Chim.*, **22** [131] 211–27 (1938); abstracted in *Verre & Silicates Ind.*, **9** [34] 395 (1938); *Ceram. Abs.*, **18** [4] 102 (1939).
9. M. C. Booze, "Fire-Clay Brick for the Open Hearth," *Jour. Amer. Ceram. Soc.*, **7** [9] 686–90 (1924).
10. M. C. Booze and F. C. Flint, "Checker-Brick for Resisting Alkaline Slags," *ibid.*, **7** [8] 594–98 (1924).
11. E. J. C. Bowmaker, "Method of Testing Probable Durability of Tank Blocks," *Jour. Soc. Glass Tech.*, **13** [50] 130–40 (1929); *Ceram. Abs.*, **9** [5] 353 (1930).
12. J. J. Brennan, "Effect of Coal Ash on Refractories," *Combustion*, **10**, 418–22 (1924); *Ceram. Abs.*, **3** [10] 289 (1924).
13. G. H. Brown, "Method of Testing Corrosive Action of Slags on Firebrick," *Trans. Amer. Ceram. Soc.*, **18**, 277–81 (1916).
14. P. P. Budnikov, "Determining Slag Resistance of Refractories," *Trudy Kharkov. Khim.-Tekh. Inst.*, No. 1, pp. 34–50 (1939); *Ceram. Abs.*, **19** [3] 67 (1940).
15. P. P. Budnikov, "Testing Stability Against Slag," *Bldg. Materials*, No. 4, pp. 35–42 (1930); *Feuerfest*, **6** [11] 169 (1930); *Ceram. Abs.*, **10** [4] 274 (1931).
16. P. P. Budnikov and S. A. Zhikharevich, "Choice of Chemically Resistant Refractory Materials for Sodium Sulfide Furnaces," *Trans. Ceram. Soc.* [England], **33**, 368–78 (1934); *Ceram. Abs.*, **14** [4] 94 (1935).
17. J. H. Chesters and T. W. Howie, "Fire-Clay Brick for Use in Iron- and Steel-Works," *Trans. Brit. Ceram. Soc.*, **38** [2] 131–51 (1939); *Ceram. Abs.*, **18** [7] 183 (1939).
18. J. H. Chesters and L. Lee, "Slag Resistance of Steelworks Refractories," *Trans. Ceram. Soc.* [England], **35** [6] 271–83 (1936); *Chem. Abs.*, **30** [18] 6519 (1936); *Ceram. Abs.*, **16** [1] 24 (1937).
19. J. H. Chesters and T. R. Lynam, "Chrome-Magnesite Brick for Open-Hearth Furnaces," *Jour. Amer. Ceram. Soc.*, **22** [4] 97–104 (1939).
20. F. H. Clews, A. Chadeyron, and A. T. Green, "Action of Alkalis on Refractory Materials: IV, Action of Potassium Chloride Vapor on Refractory Materials at 1000°C. in the Presence of Water-Vapour and Air," *Refrac. Materials Joint Comm., Inst. Gas Engrs., 26th Rept.*, pp. 24–34 (1935); *Ceram. Abs.*, **15** [10] 301 (1936).
21. F. H. Clews, A. Green, and A. T. Green, "Action of Alkalis on Refractory Materials: I, Action of Potash Vapour on Refractory Materials at 900° and 1000°C.," *Bull. Brit. Refrac. Research Assn.*, No. 32 (Oct., 1933); reprinted in *Trans. Ceram. Soc.* [England], **34** [10] 436–55 (1935); *Ceram. Abs.*, **15** [7] 207 (1936).
22. F. H. Clews, A. Green, and A. T. Green, "Action of Alkalis on Refractory Materials, II," *Refrac. Materials Joint Sub-Comm., Inst. Gas Engrs., 25th Rept.*, pp. 41–50 (1934); *Ceram. Abs.*, **14** [11] 278 (1935); same subtitle as reference 23.
23. F. H. Clews, A. Green, and A. T. Green, "II, Action of Potassium Chloride Vapour on Refractory Materials at 1000°C.," *Trans. Ceram. Soc.* [England], **36** [4] 217–24 (1937); *Ceram. Abs.*, **17** [2] 69 (1938).
24. F. H. Clews, A. Green, and A. T. Green, "III, Volatilization from Alkali-Impregnated Refractory Materials at 1000° and 1100°C.," *Refrac. Materials Joint Sub-Comm., Inst. Gas Engrs., 25th Rept.*, pp. 50–55 (1934); *Trans. Ceram. Soc.* [England], **36** [4] 225–32 (1937); *Ceram. Abs.*, **17** [2] 69 (1938).
25. F. H. Clews and A. T. Green, "Action of Alkalis on Refractory Materials: V, Further Observations on Action of Potassium Chloride Vapour on Refractory Materials at

1000°C.," *Refrac. Materials Joint Comm., Inst. Gas Engrs., 27th Rept., Commun.*, No. 143, pp. 33–41 (1936); *Ceram. Abs.*, **16** [5] 150 (1937).

26. F. H. Clews and A. T. Green, "Action of Alkalis on Refractory Materials: Summary of Parts I–IX," *Iron & Steel Inst. Special Rept.*, No. 26. pp. 359–84 (1939).

27. F. H. Clews, H. M. Richardson, A. Chadeyron, and A. T. Green, "VI, Action of Vapours of a Potash-Silica Glass on Refractory Materials at 1200°C.," *Refrac. Materials Joint Comm., Inst. Gas Engrs., 27th Rept.*, pp. 42–49 (1936); *Ceram. Abs.*, **16** [5] 150 (1937).

28. F. H. Clews, H. M. Richardson, and A. T. Green, "Action of Alkalis on Refractory Materials: VIII, Aspects of Action of Alkali Chloride Vapours on Refractory Materials at 1000°C.," *Refrac. Materials Joint Comm., Inst. Gas Engrs., 28th Rept.*, pp. 32–38 (1937); *Ceram. Abs.*, **17** [2] 69 (1938).

29. F. H. Clews, H. M. Richardson, and A. T. Green, "Action of Alkalis on Refractory Materials: IX, Experiments on Action of Vapour from Sodium Aluminate and Sodium Carbonate at Various Temperatures," *Refrac. Materials Joint Comm., Inst. Gas Engrs., 28th Rept.*, pp. 38–44 (1937); *Ceram. Abs.*, **17** [2] 69 (1938).

30. F. H. Clews, H. M. Richardson, and A. T. Green, "Action of Alkalis on Refractory Materials: X, Examinations of Reactions of NaCl Vapour with Refractory Materials at 1000°C., and Conditions Leading to Volatilization of Brick Constituents; XI, Experiments on Alterations in Strength When Refractory Materials Are Exposed to KCl Vapour at 1000°C.," *Refrac. Materials Joint Comm., Inst. Gas Engrs., 29th Rept., Commun.*, No. 193, pp. 9–20 (Nov., 1938); *Iron & Steel Inst. Special Rept.*, No. 26, pp. 385–400 (1939); *Ceram. Abs.*, **18** [8] 211 (1939).

31. E. A. Coad-Pryor, "Notes on Pot Attack," *Jour. Soc. Glass Tech.*, **2**, 285–87 (1918).

32. J. W. Cobb and Committee, "Standardization of Tests for Refractory Materials," *Trans. Ceram. Soc.* [England], **18**, 516–17 (1919).

33. H. B. Cronshaw, "Standardization of Refractory Materials Used in Iron and Steel Industries," *Trans. Faraday Soc.*, **12**, 252 (1917).

34. A. H. B. Cross and W. J. Rees, "Further Investigations of Basic Refractories for Steel-Melting Furnaces, I," *Trans. Ceram. Soc.* [England], **33**, 379–443 (1934); *Ceram. Abs.*, **13** [8] 211 (1934).

35. A. J. Dale, "Testing Refractory Materials for Resistance to Slag Corrosion and Erosion," *Trans. Ceram. Soc.* [England], **25** [4] 326–38 (1926); *Ceram. Abs.*, **6** [10] 445 (1927).

36. P. S. Dear, "Soda-Ash Foundry-Slag Attack on Refractory Lining of Teapot-Type Reservoir Ladle," *Bull. Amer. Ceram. Soc.*, **18** [1] 4–8 (1939).

37. A. E. Dodd, "Action of Slags on Refractories and Some Methods of Testing," *Trans. Ceram. Soc.* [England], **36** [2] 63–73 (1937); *Ceram. Abs.*, **16** [9] 275 (1937).

38. A. E. Dodd and A. T. Green, "Refractories Used in Production of Steel by Basic Open-Hearth Process: II, Casting Pit Refractories," *Iron & Steel Inst. Special Rept.*, No. 26, pp. 115–46 (1939); *Ceram. Abs.*, **19** [6] 142 (1940).

39. C. K. Donoho and J. T. MacKenzie, "Effect of Fluxes on Cupola Linings," *Bull. Amer. Ceram. Soc.*, **17** [8] 317–21 (1938).

40. K. Endell, "Slagging Process of Refractory Brick," *Ber. deut. keram. Ges.*, **19** [12] 491–513 (1938); *Chem. Abs.*, **33** [6] 2300 (1939); *Ceram. Abs.*, **19** [8] 191 (1940).

41. K. Endell, R. Fehling, and R. Kley, "Influence of Fluidity, Hydrodynamic Characteristics, and Solvent Action of Slag on Destruction of Refractories at High Temperature," *Jour. Amer. Ceram. Soc.*, **22** [4] 105–16 (1939).

42. K. Endell and C. Wens, "Relation Between Attack on Fire Clay and Density and Fluidity of Glasses and Slags at High Temperatures," *Glastech. Ber.*, **13** [3] 78–86 (1935); *Ceram. Abs.*, **15** [1] 15 (1936).

43. K. Endell and C. Wens, "Temperature-Viscosity Relationships of Coal Slags: I, Methods of Investigation and Results," *Z. Ver. deut. Chem. (Beiheft)*, No. 12; abstracted in *Angew. Chem.*, **48**, 76–77 (1935); *Ceram. Abs.*, **17** [5] 202 (1938); for Part II, see Rosin and Fehling, reference 136.

44. S. English, "Natural Sillimanite as Glass Refractory Material," *Jour. Soc. Glass Tech.*, **7** [27] 253–54 (1923); *Ceram. Abs.*, **3** [3] 68 (1924).

45. W. L. Fabianic, "Observations on Slagging of Some Glass Furnace Checkers," *Jour. Amer. Ceram. Soc.*, **22** [10] 337–42 (1939).

46. L. R. Faulkner, "Slagging Action of Fuel-Oil Ash," *Bull. Amer. Ceram. Soc.*, **13** [2] 45–46 (1934).

47. R. H. Fehling, "Erosion of Refractories by Coal Slag," *Jour. Inst. Fuel*, **11** [59] 451–58 (1938); *Ceram. Abs.*, **18** [6] 155 (1939).

48. R. F. Ferguson, discussion on "Slag Test and Action of Slag on Silica, Magnesite, Chrome, Diaspore, and Fire-Clay Refractories," *Bull. Amer. Ceram. Soc.*, **2** [9] 307–308 (1923); for article, see reference 82.

49. R. F. Ferguson, "Review of Literature on Laboratory Slag Tests for Refractories," *Jour. Amer. Ceram. Soc.*, **11** [2] 90–98 (1928).

50. C. R. Fettke and W. E. Stewart, "Slagging Action of Western Pennsylvania Coals on Different Types of Refractories in Small Pulverized Coal Installation," *Carnegie Inst. Tech., Mining and Met. Invest., Coop. Bull.*, No. 73, 90 pp. (1936); *Ceram. Abs.*, **17** [1] 24 (1938).

51. A. C. Fieldner, "Annual Report of Research and Technological Work on Coal, Fiscal Year 1938; Studies of Slag-Forming and Ash-Fusion Properties," *Bur. Mines Information Circ.*, No. 7052, pp. 24–26 (1939).

52. E. M. Firth, F. W. Hodkin, D. Turner, and W. E. S. Turner, "Corrosion of Fire Clay by Alkali-Lead Oxide Glasses," *Jour. Soc. Glass Tech.*, **7** [27] 218–27 (1923); *Ceram. Abs.*, **3** [3] 68 (1924).

53. E. M. Firth, F. W. Hodkin, and W. E. S. Turner, "Effect of Saltcake in Soda-Lime Batches in Corroding Fire-Clay Refractory Materials," *Jour. Soc. Glass Tech.*, **7** [27] 228–37 (1923); *Ceram. Abs.*, **3** [3] 69 (1924).

54. H. D. Fisher, "Looking for a Brick," *Combustion*, **2** [2] 12-15 (1920).

55. M. L. Freed, "Study of Mullite Refractories Formed by Calcining Cyanite, Their Industrial Application," *Jour. Amer. Ceram. Soc.*, **9** [5] 249–56 (1926); p. 255.

56. "Functions of Plant Laboratory Increase for Refractories," *Brick & Clay Rec.*, **89**, 262–65 (1936).

57. R. F. Geller, "Laboratory Testing of Aluminous Refractories," *Jour. Amer. Ceram. Soc.*, **7** [9] 663–81 (1924).

58. R. F. Geller, "Testing Fire-Clay Brick with Coal-Fired Boiler Setting," *Bur. Stand. Tech. Paper*, No. 279, 42 pp. (1925); *Ceram. Abs.*, **4** [6] 178; [11] 311 (1925).

59. German Standard Slag Test, D.I.M. 1069, July, 1931.

60. P. Gilard, "Tests for Slagging of Refractory Materials," *Rev. universelle des mines de Liége*, [Series 7], **4** [5] 281 (1924).

61. J. H. Gill, "Tests on Mullite Refractories," *Ceram. Ind.*, **8** [1] 47–48 (1927); *Ceram. Abs.*, **6** [3] 105 (1927).

62. R. S. Haff, P. S. Dear, and J. W. Whittemore, "Corrosion of Refractories by Soda-Ash Foundry Slag," *Bull. Virginia Polytech. Inst., Eng. Expt. Sta.*, No. 38, 26 pp. (1939); *Ceram. Abs.*, **19** [6] 143 (1940).

63. J. E. Hankinson, discussion on "Boiler-Furnace Refractories" by E. B. Powell, *Trans. Amer. Soc. Mech. Eng.*, **47**, 931–41 (1925); for article, see reference 127.

64. F. Hartmann, "Action of Alkalis on Refractory Brick," *Stahl u. Eisen*, **57**, 1017–22 (1937); *Ceram. Abs.*, **17** [5] 185 (1938).

65. F. Hartmann, "Method for Quantitative Determination of Action of Slag and Flue Dust on Refractory Brick," *Ber. Werkstoffausschuss. Ver. deut. Eisenhüttenleute*, No. 81 (1926); *Stahl u. Eisen*, **47** [5] 182–86 (1927); *Ceram. Abs.*, **6** [5] 178 (1927).

66. Fritz Hartmann, "Viscosity of Siemens-Martin Slag," *Arch. Eisenhüttenwesen*, **10** [2] 47–52 (1937); *Ceram. Abs.*, **17** [1] 45 (1938).

67. F. Hartmann, "Viscosity of Slags and Its Applica-

tion to Slagging of Refractory Brick," *Ber. deut. keram. Ges.*, **15** [7] 375–90 (1934); *Ceram. Abs.*, **14** [5] 119 (1935); see also references 37, 41, 43, 47, 51, 66, 84, 97, 121, 136.

68. R. A. Hay, B. McIntosh, J. R. Rait, and J. White, "Slag Systems: FeO–Al_2O_3 and FeO–MnO–Al_2O_3," *Jour. West Scot. Iron & Steel Inst.*, **44** [6] 85–92 (1937); *Ceram. Abs.*, **17** [5] 202 (1938).

69. O. Hebestreit, "Dependence of Slagging of Firebrick on Flux Content and Porosity." Dissertation of the Technischen Hochschule, Aachen, 1930.

70. C. H. Herty, Jr., "Slag Viscosity Control," *Blast Furnace & Steel Plant*, **25** [9] 1000–1001 (1937); see also reference 38.

71. F. Hessinger, "Methods of Testing Tank Brick," *Sprechsaal*, **70** [16] 211–12 (1937); *Ceram. Abs.*, **16** [9] 276 (1937).

72. R. P. Heuer, "Petrographic, Fusion, and Slag Studies of Magnesite Refractories in Rotary Kiln Service," *Rock Prod.*, **37** [12] 42–46 (1934); *Ceram. Abs.*, **14** [3] 72 (1935).

73. L. C. Hewitt, "Fusion Points of Firebrick Coal-Ash Mixtures," *Jour. Amer. Ceram. Soc.*, **9** [9] 575–82 (1926).

74. H. Hirsch, "Slag Action on Refractory Linings," *Tonind. Ztg.*, **47**, 152–54 (1923); *Ceram. Abs.*, **2** [6] 131 (1923).

75. M. Hirsch, "Attack on Firebrick by Slagging," *Sprechsaal*, **45** [14] 213 (1912).

76. A. W. Hixon and V. D. Leudeke, "Wall Friction in Liquid Agitation Systems," *Ind. Eng. Chem.*, **29** [8] 927–33 (1937); *Ceram. Abs.*, **17** [1] 31 (1938).

77. H. S. Houldsworth, "Some Properties of Clay-Sillimanite Mixtures," *Trans. Ceram. Soc.* [England], **24**, 33–41 (1925); *Ceram. Abs.*, **3** [12] 350 (1924).

78. R. M. Howe, "How Slag Temperatures Affect Firebrick," *Brick & Clay Rec.*, **54** [2] 143–44 (1919).

79. R. M. Howe, "Study of Slag Test," *Jour. Amer. Ceram. Soc.*, **6** [2] 466–73 (1923).

80. R. M. Howe, "Testing of Refractories," *ibid.*, **6** [1] 296–98 (1923).

81. R. M. Howe, "Tests Now in Vogue for Refractories," *Brick & Clay Rec.*, **53** [13] 1066–67 (1918).

82. R. M. Howe, S. M. Phelps, and R. F. Ferguson, "Action of Slag on Silica, Magnesite, Chrome, Diaspore, and Fire-Clay Refractories," *Jour. Amer. Ceram. Soc.*, **6** [4] 589–95 (1923); for discussion, see reference 49.

83. W. Hugill, R. L. Ainsworth, and A. T. Green, "Action of Slags on Refractories: II, Some Observations on Corrosive Action of Lime on Aluminous, Fire-Clay, and Silica Brick," *Iron & Steel Inst., Special Rept.*, No. 26, pp. 351–57 (1939); *Refrac. Materials Joint Comm., Inst. Gas Engrs. Commun., 29th Rept.*, No. 193, pp. 29–33 (Nov., 1938); *Ceram. Abs.*, **18** [8] 211 (1939).

84. W. Hugill and A. T. Green, "Action of Slags on Refractory Materials: I," *Iron & Steel Inst., Special Rept.*, No. 26, pp. 295–349 (1939); same subtitle as reference 85.

85. W. Hugill and A. T. Green, "Action of Slags on Refractory Materials: I, Application of Tests to the Study of the Action of CaO–Al_2O_3–SiO_2 Slags on Refractory Materials," *Refrac. Materials Joint Comm., Inst. Gas Engrs., 28th Rept.*, pp. 44–60 (1937); *Ceram. Abs.*, **17** [2] 69 (1938).

86. R. K. Hursh, "Laboratory Slagging Test for Boiler-Furnace Refractories, FSP51-44," *Trans. Amer. Soc. Mech. Eng.*, **51** [44] 339–45 (1929); *Ceram. Abs.*, **8** [12] 887 (1929).

87. R. K. Hursh, "Laboratory Slagging-Test Furnace with Rotating Burner," *Jour. Amer. Ceram. Soc.*, **22** [10] 354–57 (1939).

88. R. K. Hursh and W. E. Welliver, "Viscosity-Temperature Characteristics of Some Coal-Ash Slags." Thesis for M.S. degree in Ceramic Engineering, University of Illinois, June, 1940.

89. R. Hustin, "Fractional Fusion of Refractories," *Chim. Ind.*, **14**, 691 (1925); *Ceram. Abs.*, **5** [12] 405–406 (1926).

90. J. F. Hyslop, "Chemical Activity of Refractories," *Jour. Soc. Glass Tech.*, **20** [78] 61–62 (1936); *Ceram. Abs.*, **15** [10] 301 (1936).

91. J. F. Hyslop and H. C. Biggs, "Corrosion of Refractories, Quantitative Durability Test," *Colliery Guardian*, **143** [3701] 1913 (1931); *Ceram. Abs.*, **11** [3] 181 (1932); *Brit. Clayworker*, **40** [477] 335–36 (1931); *Ceram. Abs.*, **11** [4] 247 (1932); also published in *Refrac. Jour.*, **8** [2] 52–54 (1932).

92. J. F. Hyslop and H. C. Biggs, "Slag and Spalling Tests on Firebrick," *Trans. Ceram. Soc.* [England], **30** [8] 288–94 (1931); *Ceram. Abs.*, **10** [12] 844 (1931).

93. J. F. Hyslop, R. Gumm, and H. Biggs, "Some Corrosion and Erosion Phenomena and Their Bearing on Macrostructure of Refractories," *Jour. Soc. Glass Tech.*, **10** [40] 405–12 (1926); *Ceram. Abs.*, **6** [6] 214 (1927).

94. F. Illgren, "Influence of Blast-Furnace Dust on Cone-Fusion Point of Clay Materials with Various Alumina Contents," *Ber. deut. keram. Ges.*, **7** [1] 32–36 (1926); *Ceram. Abs.*, **6** [6] 224 (1927).

95. H. Insley, "Notes on Behavior of Refractories in Glassmelting Furnaces," *Jour. Amer. Ceram. Soc.*, **7** [8] 583–92 (1924).

96. H. Jebsen-Marwedel, "Influence of Surface Tension of Slag Glass from Refractory Material on Its Tendency to Form Nodes and Cords, II," *Glastech. Ber.*, **15** [5] 163–73 (1937); *Ceram. Abs.*, **17** [5] 177 (1938).

97. H. Jebsen-Marwedel, "Local Reactions of Slag with Furnace Refractories," *Feuerungstech.*, **25** [3] 78–79 (1937); *Ceram. Abs.*, **16** [11] 340 (1937).

98. R. L. Johnson, "Corrosive Action of Frits on Refractories," *Pottery Gaz.*, No. 503, pp. 489–96 (1919); *Jour. Amer. Ceram. Soc.* (*Abstract Section*), **2** [10] 841 (1919).

99. C. L. Kinney, symposium on "Steel Mill Pouring Pit Refractories: IV, Steel Pouring Refractories," *Bull. Amer. Ceram. Soc.*, **18** [3] 87–92 (1939).

100. T. A. Klinefelter and E. P. Rexford, "Action of Slags on Firebrick and Boiler-Furnace Settings," *Trans. Amer. Soc. Mech. Eng.*, **53** [14] 301–305 (1931); *Ceram. Abs.*, **11** [1] 38 (1932).

101. F. A. Kohlmeyer, "Selection of Firebrick by Comparative Tests with Detailed Description of Method Used to Measure Temporary Expansion or Contraction of Firebrick at Various Temperatures," *Jour. Amer. Ceram. Soc.*, **8** [5] 313–18 (1925); p. 317.

102. L. Kollbohn, "Experience with a Slagging (Boiler) Furnace in Germany," *Feuerungstech.*, **25**, 5–7 (1937); *Chem. Abs.*, **32** [9] 2321 (1938); see also E. Rammler, reference 128.

103. H. M. Kraner, "Development of Slagging Test for Refractories," *Metals & Alloys*, **9** [4] 79–83 (1938); *Ceram. Abs.*, **17** [8] 280 (1938).

104. Y. Letort, "Mechanism of Corrosion of Refractory Cupola Linings," *Bull. Assn. Tech. Fonderie*, **13**, 248–57 (1939); *Brit. Chem. & Phys. Abs.–B*, **58** [11] 1118 (1939); *Ceram. Abs.*, **19** [3] 68 (1940).

105. L. Litinsky, "Development of Refractories Containing Magnesia," *Ber. deut. keram. Ges.*, **16** [11] 565–96 (1935); *Brick & Clay Rec.*, **98** [5] 212–18 (1936); *Ceram. Abs.*, **15** [9] 276 (1936).

106. H. H. Macey and F. H. Clews, "Measurement of Apparent Porosity," *Refrac. Materials Joint Comm., 29th Rept., Inst. Gas Engrs., Commun.*, No. 195, pp. 45–52 (Nov., 1938); *Ceram. Abs.*, **18** [8] 213 (1939).

107. J. S. McDowell and R. M. Howe, "Basic Refractories for Open Hearth," *Bull. Amer. Inst. Mining Eng.*, **146**, 291–309 (1919); *Trans. Amer. Inst. Mining Eng.*, **62**, 90 (1919); *Blast Fur. & Steel Plant*, **7**, 227 (1919).

108. S. J. McDowell and H. C. Lee, "Petrographic Study of Some Slags from Boiler Furnaces," *Jour. Amer. Ceram. Soc.*, **11** [1] 35–41 (1928).

109. J. C. McMullen, "New Slag Test Furnace," *Bull. Amer. Ceram. Soc.*, **19** [11] 439–42 (1940).

110. T. N. McVay, "Identification of Crystalline Substances by Means of the Petrographic Microscope," *ibid.*, **13** [10] 255–60 (1934).

111. T. N. McVay and R. K. Hursh, "Effects of Coal Ash on Refractories," *Jour. Amer. Ceram. Soc.*, **11** [11] 868–73 (1928).

112. J. W. Mellor, "Action of Flue Dust on Firebrick," *Trans. Ceram. Soc.* [England], **13**, 12–14 (1914).

113. J. W. Mellor and W. Emery, "Corrosive Action of Flue Dust on Firebrick," *Trans. Ceram. Soc.*, [England], **18**, 230–50 (1919).

114. J. W. Mellor and A. T. Green, "Refractory Materials," *Chem. & Ind.*, **57** [27] 627–37 (1938); *Ceram. Abs.*, **18** [11] 302 (1939).

115. W. Miehr, "Standards for Testing Probable Behavior of Tank Blocks," *Jour. Soc. Glass Tech.*, **15** [57] 30–40 (1931); *Ceram. Abs.*, **10** [8] 576 (1931).

116. W. Miehr, J. Kratzert, and H. Immke, "Consideration of Resistance to Action of Slags Shown by Refractory Materials," *Tonind. Ztg.*, **51** [9] 121–22 (1927); *Ceram. Abs.*, **6** [10] 449 (1927).

117. Rudolf Miksch and Hermann Salmang, "Investigations on Slagging of Refractory Materials: III, Slagging of Magnesite," *Arch. Eisenhüttenwesen*, **3**, 313–18 (1929); *Ceram. Abs.*, **9** [5] 357 (1930).

118. O. V. Nefedieva and N. B. Pacukov, "Laboratory Tests of Chemical Activity of Ashes of Solid Fuels in Relation to Refractories," *Izvestia Teplotech. Inst.* [Moscow], **5**, 20–30 (1929); *Ceram. Abs.*, **8** [12] 894 (1929).

119. C. E. Nesbitt and M. L. Bell, "Practical Methods for Testing Refractory Firebrick," *Proc. A.S.T.M.*, **16** [Part II] 350–72 (1916); *Met. Chem. Eng.*, **15** [4] 205–12 (1916); *Brick & Clay Rec.*, **51**, 518 (1917).

120. F. H. Norton, "Quantitative Laboratory Slag Test," *Jour. Amer. Ceram. Soc.*, **7** [8] 509–602 (1924).

121. M. Y. Ostrankov, "Temperature of Formation of Globules of Primary Blast-Furnace Slags," *Metallurg*, **12** [4] 80–90 (1937); *Jour. Iron & Steel Inst.*, **137** [1] 311A (1938); *Ceram. Abs.*, **18** [3] 87 (1939).

122. C. W. Parmelee, unpublished data.

123. J. H. Partridge and H. C. Biggs, "Glasshouse Refractories, Study of Corrosion-Resisting Properties," *Jour. Soc. Glass Tech.*, **14** [53] 63–84 (1930); *Ceram. Abs.*, **9** [9] 743 (1930).

124. W. E. Patterson, "Practical Tests on Refractory Mixes," *Jour. Can. Ceram. Soc.*, **6**, 38–44 (1937); *Ceram. Abs.*, **17** [1] 21 (1938).

125. M. F. Peters, "Carborundum Brick," *Jour. Amer. Ceram. Soc.*, **5** [4] 181–208 (1922).

126. G. R. Pole and D. G. Moore, "Testing Refractories Against Corrosive Action of Electric-Furnace Phosphate Slags," *ibid.*, **19** [10] 259–70 (1936).

127. E. B. Powell, "Boiler-Furnace Refractories," *Trans. Amer. Soc. Mech. Eng.*, **47**, 881–87, 912–13 (1925); *Ceram. Abs.*, **5** [10] 335 (1926); for discussion, see reference 63.

128. E. Rammler, "Experience with Slagging (Boiler) Furnace in Czechoslovakia," *Feuerungstech.*, **25**, 7–14 (1937); *Chem. Abs.*, **32** [9] 2321 (1938); see also J. Kollbohn, reference 102.

129. W. J. Reagan, "Open-Hearth Slag Control," *Iron Age*, **144** [7] 31–38 (1939); *Ceram. Abs.*, **19** [1] 15 (1940).

130. W. J. Rees, "Slag Resistance," *Claycraft*, **9** [9] 409 (1936); *Ceram. Abs.*, **15** [10] 303–304 (1936).

131. G. Rigg, "Refractory Materials," *Jour. Soc. Chem. Ind.*, **33** [12] 623 (1914); *Ind. Eng. Chem.*, **5**, 549 (1913).

132. W. F. Rochow, "Refractories and Their Applications," *Trans. Amer. Inst. Chem. Eng.*, **31** [2] 228–48 (1935); *Ceram. Abs.*, **17** [6] 222 (1938).

133. W. F. Rochow and J. S. McDowell, "Choosing Refractories for Superstructure and Regenerators of Modern Glass Tanks: I, Refractories and Insulating Materials," *Amer. Glass Rev.*, **57** [38] 9–12; "II, Refractories in the Glasshouse," *ibid.*, [39] 9–12; [40] 9–12 (1938); *Ceram. Abs.*, **17** [11] 354 (1938).

134. C. I. Rose, "Proposed Method for Studying Attack of Molten Slags and Glasses on Refractory Materials," *Jour. Amer. Ceram. Soc.*, **6** [12] 1242–47 (1923).

135. Walter Rosenhain, "Some Phenomena of Pot Attack," *Jour. Soc. Glass Tech.*, **3**, 93–116 (1919).

136. P. Rosin and R. Fehling, "Temperature-Viscosity Relationships of Coal Slags: II, Conclusions for Firing Techniques," *Z. Ver. deut. Chem.* (*Beiheft*), No. 12; abstracted in *Angew. Chem.*, **48**, 76–77 (1935); *Ceram. Abs.*, **17** [5] 202 (1938); for Part I, see K. Endell and C. Wens, reference 43.

137. N. V. Rulla, "Viscosity of Blast-Furnace Slags," *Teoriya & Prakt. Met.*, **9** [11] 20–37 (1937); *Chem. Abs.*, **32** [5] 1625 (1938); *Ceram. Abs.*, **17** [6] 234 (1938).

138. S. Sachs, "Testing Attack of Slag," *Tonind. Ztg.*, **58** [98] 1195–97 (1934); *Ceram. Abs.*, **14** [5] 119 (1935).

139. Hermann Salmang, Die physikalischen und chemischen Grundlagen der Keramik (Physical and Chemical Principles of Ceramics), pp. 167–76. Julius Springer, Berlin, 1933. 229 pp.; *Ceram. Abs.*, **13** [4] 103 (1934).

140. Hermann Salmang, "Investigation of Slagging of Refractory Material," *Stahl u. Eisen*, **47** [43] 1816–20 (1927); *Ceram. Abs.*, **7** [2] 85 (1928).

141. Hermann Salmang and Otto Hebestreit, "Dependence of Scorifying of Grog Blocks on Flux Content and Porosity, V," *Feuerfest*, **7** [1] 1–8 (1931); *Ceram. Abs.*, **10** [5] 353 (1931).

142. Hermann Salmang and Joseph Kaltenbach, "Researches on Scorification of Refractory Materials: VI, Investigations on Power of Corrosion and Constitution of Smeltery Slag," *Feuerfest*, **7** [11] 161–69 (1931); *Ceram. Abs.*, **11** [3] 179 (1932).

143. Hermann Salmang and Friedrich Schick, "Investigations of Corrosion of Refractory Materials: II, Influence of Chemical Composition of Slags," *Arch. Eisenhüttenwesen*, **2**, 439–47 (1929); *Ceram. Abs.*, **8** [12] 890 (1929).

144. Hermann Salmang and Friedrich Schick, "Scorification of Refractory Materials: III–IV, *Arch. Eisenhüttenwesen*, **2**, 98 (1928–1929); **4**, 299–316 (1930–1931); *Stahl u. Eisen*, **50** [52] 1814 (1930); *Ceram. Abs.*, **10** [5] 353 (1931).

145. J. Schaefer, "Determining Resistance of Refractories to Action of Slag," *Tonind. Ztg.*, **54** [76] 1223–25 (1930); *Ceram. Abs.*, **9** [12] 1051 (1930).

146. J. Schaefer and F. Baumhauer, "Influence of Slag on Refractory Block," *Feuerfest*, **7** [3] 33–36 (1931); *Ceram. Abs.*, **10** [8] 576 (1931); *Chem. Abs.*, **25** [14] 3791 (1931).

147. T. Schauer, "Slag Penetration in Refractory Block," *Sprechsaal*, **72** [47] 553–54 (1939); *Ceram. Abs.*, **19** [4] 92 (1940).

148. E. H. Schulz, "Studying and Testing Refractory Materials for Metallurgical Industry in Germany," *Stahl u. Eisen*, **45**, 1733 (1925); p. 1777; *Ceram. Abs.*, **5** [12] 406 (1926).

149. H. G. Schurecht, "Reactions of Slag with Refractories: I, Surface Reactions," *Jour. Amer. Ceram. Soc.*, **22** [4] 116–23 (1939).

150. R. A. Sherman, "Study of Refractories Service Conditions in Boiler Furnaces," *U. S. Bur. Mines Bull.*, No. 334, 144 pp. (1931); *Ceram. Abs.*, **10** [6] 438 (1931).

151. H. E. Simpson, "Classified Review of Refractory Slag Tests," *Jour. Amer. Ceram. Soc.*, **15** [10] 536–44 (1932).

152. H. E. Simpson, "Investigation of Action of Coal-Ash Slags on Firebrick by Microscopic Methods," *ibid.*, **15** [10] 520–35 (1932).

153. V. Škola, "Combined Testing Methods," *Ber. deut. keram. Ges.*, **13** [14] 167–74 (1932); *Ceram. Abs.*, **11** [9] 506 (1932).

154. F. D. Starostin, "Determination of Resistance of Silica Brick to Slag," *Ogneupory*, **5** [9] 678–84 (1937); *Ceram. Abs.*, **18** [3] 75 (1939).

155. W. E. Stewart, "Slag Attack on Refractory Brick," *Brick & Clay Rec.*, **91**, 144–46 (1937); *Chem. Abs.*, **31** [21] 8142 (1937); see also C. R. Fettke and W. E. Stewart, reference 50.

156. G. C. Stone, "Discussion on Refractory Firebrick," *Proc. A.S.T.M.*, **16** [Part II] 374–75 (1916).

157. Wilber Stout, "Relations Between Manufacture and Properties of Refractory Clayware," *Trans. Amer. Ceram. Soc.*, **14**, 250–55 (1912); p. 252.

158. B. W. Stromberg, "Furnace-Testing Refractories for Slag Erosion," *Chem. Met. Eng.*, **37** [11] 685–86 (1930); *Ceram. Abs.*, **10** [2] 123 (1931).

159. W. C. Taylor, "Phase Equilibria Studies on Mixtures of the Compounds $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$–$2CaO \cdot Fe_2O_3$–$K_2O \cdot Al_2O_3$," *Jour. Research Nat. Bur. Standards*, **21** [3] 315–25 (1938); R.P. 1131; *Ceram. Abs.*, **18** [1] 36 (1939).

160. C. W. Thomas, discussion on "Testing Refractory Materials," by J. W. Mellor, *Trans. Ceram. Soc.* [England], **17**, 100–102 (1918).

161. H. V. Thompson, "Dissociation of Salt," *ibid.* **17**, 340–50 (1918).

162. Donald Turner and W. E. S. Turner, "Some Observations on Corrosion of Fire-Clay Materials by Alkali Salts," *Jour. Soc. Glass Tech.*, **7** [27] 207–18 (1923); *Ceram. Abs.*, **3** [3] 68 (1924).

163. A. E. J. Vickers and R. A. Bell, "Apparatus for Investigating Corrosive Action of Slags on Refractory Materials," *Jour. Soc. Glass Tech.*, **19**, 151–55 (1935); *Ceram. Abs.*, **16** [7] 206 (1937).

164. L. M. Wilson, "Effect of Salty Coal on Refractory Materials," *Trans. Ceram. Soc.* [England], **23**, 39–50 (1924); *Ceram. Abs.*, **3** [10] 288 (1924).

165. H. Wilson, C. E. Sims, and F. W. Schroeder, "Artificial Sillimanite as a Refractory, II," *Jour. Amer. Ceram. Soc.*, **7** [12] 907–19 (1924).

166. Hewitt Wilson and K. G. Skinner, "Review of Four Years of Research on Refractory Properties of Pacific-Northwest Olivine," *ibid.*, **23** [5] 136–38 (1940).

AMERICAN REFRACTORIES INSTITUTE
MELLON INSTITUTE
PITTSBURGH, PENNSYLVANIA

ELECTRIC FURNACE STUDY OF THE MgO–SiO_2 SYSTEM*

BY ROBERT R. RALSTON AND GEORGE T. FAUST†

ABSTRACT

Fusions of compositions spaced at intervals throughout the magnesia–silica system were prepared in an electric arc furnace. Potter's flint and precipitated magnesium carbonate were used as starting materials for one series of samples, and olivine, quartz sand, and magnesite were used as lower purity raw materials in a second series to simulate commercial conditions. Chemical, spectrographic, microscopic-petrographic, density, and pyrometric cone equivalent (P.C.E.) determinations were made on typical specimens selected from each melt. Periclase, forsterite, and clinoenstatite crystallized in strict agreement with the phase diagram, and the phenomenon of immiscible silicate phases was observed in high silica compositions. No new compounds, however, were seen. The possibility of beneficiating olivine for refractory service by electric furnacing was also investigated.

I. Introduction

The magnesia–silica system has been the subject of numerous investigations from the viewpoint of phase equilibrium as well as from the relation of refractory service to the consumer. Bowen and Andersen[1] studied the system to the limit of their wire-wound furnaces and showed that forsterite and clinoenstatite are the only binary compounds. Greig[2] completed the system for the higher temperatures and the region of silicate immiscibility (see Fig. 1). Bowen and Schairer,[3] who extended their investigation to the ternary system MgO–FeO–SiO_2, applied the term "magnesio-wüstite" to the series of solid solutions of MgO and FeO. All of these workers were interested primarily in significant compositions under equilibrium conditions in order to indicate the phase diagram precisely, and their equi-

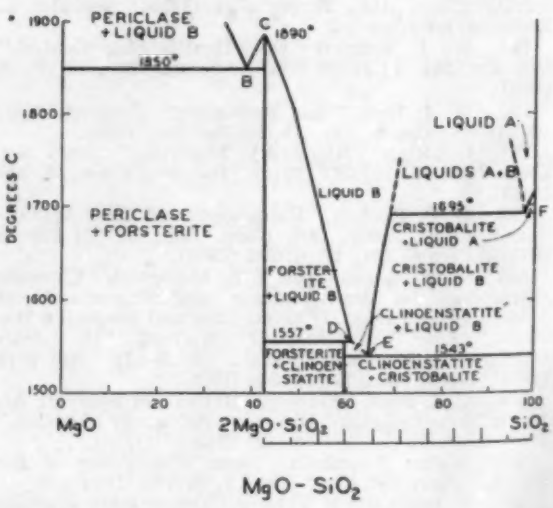

FIG. 1.—MgO–SiO_2 system (after Bowen and Andersen[1] and revised by J. W. Greig).

* Presented at the Forty-Third Annual Meeting, The American Ceramic Society, Baltimore, Md., April 2, 1941 (Refractories Division). Preliminary copy received April 9, 1941; printer's copy received January 7, 1942.

Published by permission of the Director, Bureau of Mines, U. S. Department of the Interior.

† The authors are, respectively, electrochemical engineer at the Bureau of Mines Electrotechnical Laboratory, U. S. Department of the Interior, Norris, Tenn., and assistant chemist-petrographer, formerly at the Bureau of Mines, Southern Experiment Station, Tuscaloosa, Ala.

[1] N. L. Bowen and O. Andersen, "Binary System MgO–SiO_2," *Amer. Jour. Sci.*, [4th Series] **37**, 487–500 (1914).

[2] J. W. Greig, "Immiscibility in Silicate Melts, I–II," *ibid.*, [5th Series] **13** [73] 1–44; [74] 133–54 (1927); *Ceram. Abs.*, **6** [4] 157 (1927).

[3] N. L. Bowen and J. F. Schairer, "System MgO–FeO–SiO_2," *Amer. Jour. Sci.*, [5th Series] **29**, 151–217 (1935); *Ceram. Abs.*, **15** [9] 288 (1936).

TABLE I

CHEMICAL ANALYSIS OF INGREDIENTS OF FUSIONS

	Flint*	Magnesium carbonate†	Olivine‡	Calcined magnesite§	Quartz sand‖
Ignition loss	0.1	**	1.4	3.50	0.13
Carbon dioxide	**	36.50	**	**	**
Silica	99.1	0.20	42.6	1.20	99.00
Alumina	0.4	0.10	1.5	0.22	0.18
Titania	**	**	**	**	.23
Zirconia	**	**	**	**	.04
Ferric oxide	0.02	0.02	8.0	0.46	.34
Calcium oxide	**	**	0.1	1.81	.18
Magnesia	**	42.40	46.6	92.81 (diff.)	.11
Sodium oxide	0.1	**	**	**	**
Potassium oxide	0.2	0.15	**	**	**
Combined water	**	20.30	**	**	**
Water-soluble salts	**	0.33	**	**	**

* Analysis by E. W. Koenig, chief chemist, Consolidated Feldspar Corp., Erwin, Tenn.
† Analysis by the R. & H. Chemicals Dept., E. I. du Pont de Nemours & Co.
‡ Analysis by J. E. Boyd, chief chemist, United Feldspar & Minerals Corp., Spruce Pine, N. C.
§ Analysis by General Magnesite & Magnesia Co., Philadelphia, Pa.
‖ Analysis by E. E. Conitz, Southern Experiment Station, Bureau of Mines, Tuscaloosa, Ala.
** Not reported.

librium data have been invaluable in planning and interpreting results obtained in commercial practice.

When refractory compositions are compounded from two or more ingredients, however, and are bonded and fired at temperatures usually far below complete melting, equilibrium conditions are usually approached very sluggishly and frequently are not achieved even after years of exposure to service conditions. Any treatment that converts the low-melting components of a heterogeneous system into higher-melting, stable compounds should obviously result in the improvement in refractory properties.

To approach equilibrium as closely and as quickly as possible, compositions of the MgO–SiO_2 system were completely melted, and the products were allowed to crystallize from the homogeneous molten mass at temperatures where reactions proceed at greatly accelerated rates. Early experiments at Norris have shown that the crystallization of forsterite from a magnesia-silica melt is rapid and that large, well-developed crystals form within a few minutes.

II. Magnesia-Flint Series

Two distinct series of magnesia-silica melts were prepared. The first, designated as the magnesia-flint series, comprised fusions of potter's flint (pulverized primary quartz) and magnesia (calcined, precipitated magnesium carbonate) whose compositions are given in Table I. This group of samples was intended to provide reliable petrographic specimens for comparison with the other less pure melts although it does not necessarily represent a grade of extremely high purity.

The flint and magnesium carbonate were weighed as 35- to 60-lb. batches, thoroughly mixed by hand, and calcined to 900° to 1000°C. to provide calculated compositions (see Table II). The purpose of calcining the mixture was (1) to eliminate evolution of CO_2, which tended to blow the powdery charge from the furnace, (2) to sinter the ingredients lightly together, thereby minimizing segregation and dusting, and (3) to prevent reaction of the CO_2 on the graphite electrodes ($CO_2 + C = 2CO$).

TABLE II

FURNACE CHARGES FOR MAGNESIA-FLINT SERIES

	Furnace charge (lb.)		Calculated final composition (%)	
Sample No.	Flint	$MgCO_3$	MgO	SiO_2
60-R	26.4	13.2	17.5	82.1
61	24.7	16.6	22.2	77.5
62	23.1	19.8	26.7	73.0
63	22.1	21.8	29.5	70.2
64	21.4	23.2	31.5	68.1
65	20.5	25.0	34.1	65.6
66	14.9	36.2	50.7	48.7
16-A	8.9	24.1	53.4	46.4
67	13.2	39.6	55.9	43.8
68	12.4	41.2	58.4	41.3
69	9.9	46.2	66.3	33.5
70	6.6	52.8	76.9	22.8
71	3.3	59.4	88.0	11.8

Copious white fumes were expelled while the charges were in the furnace, and this loss of material was expected to produce discrepancies between the calculated and determined final compositions. Both silica and magnesia are known to have appreciable vapor pressures at the temperatures involved, and both were probably present in the expelled vapors. Sosman[4] states that the loss of silica may be particularly severe under reducing conditions.

III. Olivine-Magnesite-Quartz Series

The second series was designated as the olivine-magnesite-quartz series because commercially available raw materials were used in its preparation (Table I). The magnesia-enriched compositions were derived by additions of calcined magnesite.

[4] R. B. Sosman, Properties of Silica, pp. 106–11. American Chemical Society Monograph Series, No. 37; Chemical Catalog Co., Inc., New York, N. Y., 1927; *Ceram. Abs.*, 7 [7] 505 (1928).

FIG. 2.—Arc furnace in which melts were prepared; lower 2-in. graphite electrode enters through transite insulating disk in pot bottom; upper electrode is adjustable vertically; the charge is fed to smothered arc as melting proceeds.

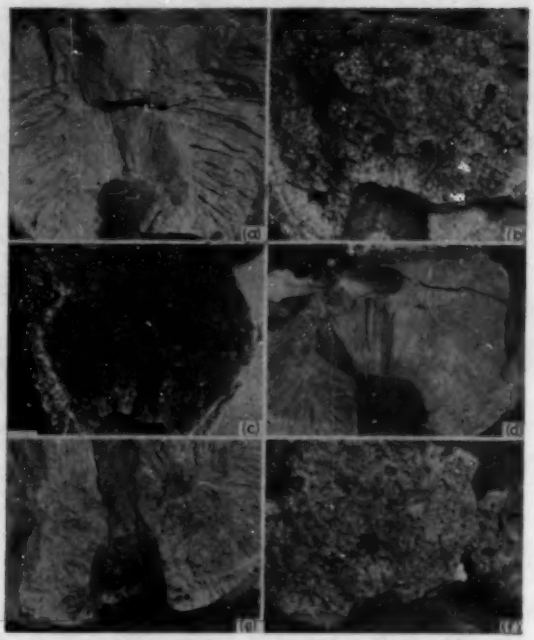

FIG. 3.—(*a*) Typical appearance of melts in olivine-quartz sand series; *melt No. 38-A:* MgO 33.8% and SiO_2 62.2%; note broken end of 2-in. graphite electrode; ferrosilicon globules appear in lowest portion of melt.

(*b*) *Melt No. 46-A:* MgO 56.9% and SiO_2 38.3%; predominantly forsterite; note outline of 2-in. bottom electrode; globules of ferrosilicon appear scattered throughout melt; darker color typical of melts containing magnesio-wüstite.

(*c*) Typical porous structure of olivine-magnesite melts; *melt No. 48-A:* MgO 64.4% and SiO_2 29.0%.

(*d*) Typical large-grained development in high silica, flint-magnesia melts; fracture smooth and vitreous; note outline of 2-in. bottom electrode; *melt No. 60-B:* MgO 20.5% and SiO_2 77.1%.

(*e*) *Melt No. 66:* MgO 55.4% and SiO_2 42.9%; largely prismatic forsterite, synthesized from purified magnesia and flint.

(*f*) Typical porous structure of high magnesia melts derived from fusion of magnesia and flint; *melt No. 69:* MgO 65.6% and SiO_2 33.8%.

Because of the presence of iron in the olivine, a calculated amount of carbon was added in each fusion mixture for the purpose of reduction (see Table III). The carbon addition was 23% greater than that theoretically required to reduce the combined iron, chromium, and nickel to the metallic state. The carbon, furthermore, was artificially graphitized petroleum coke, which was derived from crushed electrode stubs or lathe turnings and crushed to pass an 8-mesh screen.

IV. Fusion

Fusions were carried out in a small, pot-style furnace with a stationary, 2-in. graphite electrode brought up through an opening in the bottom of the iron shell and a 2-in. electrode suspended from above and adjusted by a crank (Fig. 2). The furnace accommodated a charge of approximately 25 to 45 lb. of feed, depending on the densities of the ingredients and product.

TABLE III

FURNACE CHARGES FOR OLIVINE-MAGNESITE-QUARTZ SERIES

Sample No.	Furnace charge (lb.)				Calculated final composition (%)	
	Calcined magnesite	Olivine	Quartz sand	Carbon	MgO	SiO_2
40-B		18.0	27.0	0.3	19.5	79.6
39-A		17.5	17.5	.35	24.6	74.4
38-A		21.0	14.0	.42	29.7	69.1
37-A		24.5	10.5	.49	35.0	63.8
36-A		28.0	7.0	.56	40.3	58.2
35-A		31.5	3.5	.63	45.8	52.7
45-A		35.0		.70	51.3	46.9
46-A	3.5	31.5		.63	56.1	42.1
47-A	7.0	28.0		.56	60.8	37.4
48-A	10.5	24.5		.49	65.4	32.7
55	45.0				96.8	1.04

TABLE IV

FUSED PRODUCTS FOR MAGNESIA-FLINT SERIES

Sample No.	Chemical analysis* MgO	SiO_2	Al_2O_3	FeO	TiO_2	MnO	Cr_2O_3	NiO	CaO	Combined alkalis (as chlorides)	Specific gravity
60-R	20.53	77.06	0.38	0.15	0.005	0.008	0.02	0.05	0.12	Trace	2.60
61	22.38	75.57	.86	.36	.008	.007	.01	Trace	.11	0.35	2.65
62	29.82	68.21	.51	.46	.02	< .01	.03	0.02	.65	0.12	2.92
63	33.24	66.09	.48	.60	.013	.003	.03	Not detected	.07	†	2.93
64	36.61	62.44	.37	.10	.009	.010	.03	0.06	.12	0.30	3.08
65	38.71	60.67	.51	.27	.016	.004	Trace	Not detected	.04	†	3.15
15	51.60	48.20	.59	.26	†	†	†	†	†	†	†
66	55.41	42.91	.46	.13	.013	.004	0.02	Trace	.90	†	3.19
13-A	56.13	42.23	.58	.50	.016	.007	0.01	Trace	.13	†	3.20
67	59.84	39.67	.15	.13	.02	< .01	†	0.01	.58	0.25	3.25
68	60.43	37.03	.33	.20	.008	.009	Trace	Trace	.26	†	3.24
69	65.64	33.77	.00	.19	.02	< .01	†	0.02	.50	0.24	3.30
17	67.60	31.40	.20	.17	†	†	†	†	†	†	†
70	74.23	23.51	.14	.13	.016	.010	Trace	Trace	.40	†	3.37
71	88.68	8.21	.21	.13	.018	.011	Trace	Trace	.64	†	3.48

* E. E. Creitz, analyst, Southern Experimental Station, Bureau of Mines, Tuscaloosa, Ala.
† Not determined.

TABLE V

FUSED PRODUCTS FOR OLIVINE-MAGNESITE-QUARTZ SERIES

Sample No.	Chemical analysis* MgO	SiO_2	Al_2O_3	FeO	TiO_2	MnO	Cr_2O_3	NiO	CaO	Combined alkalis	Specific gravity
40-B	27.27	70.92	0.60	0.82	0.088	0.007	0.04	0.24	0.12	†	2.78
39-A	29.21	67.36	.70	1.90	.078	.014	.01	.01	.10	0.11	2.88
38-A	33.80	62.21	.70	1.98	.052	.014	.01	.00	.08	Trace	3.00
37-A	37.04	61.14	.36	0.46	.05	< .01	.06	.02	.06	0.20	3.15
36-A	47.78	49.69	.47	1.40	.03	< .01	.05	.03	.06	0.26	3.23
35-A	48.56	48.65	.39	1.74	.027	.017	.02	.15	.08	Trace	3.23
45-A	51.20	45.47	.54	1.83	.010	.006	.02	.35	.08	0.10	3.22
46-A	56.85	38.32	.37	3.04	.026	.027	.03	.02	.13	Trace	3.28
47-A	59.50	34.01	.45	5.63	.04	†	.16	.08	.25	0.16	3.37
48-A	64.38	29.00	.43	5.21	.04	< .01	.17	.11	.44	0.15	3.40
55	96.35	1.61	.21	0.46	.008	.007	.02	.06	.28	Trace	3.56

* E. E. Creitz, analyst, Southern Experimental Station, Bureau of Mines, Tuscaloosa, Ala.
† Not determined.

Melting began close to the arc and extended in all directions through the mix until a major portion of the available charge around the electrode was fused. More mix was added as melting progressed and the volume decreased. Fusion of the charge was complete within the zone of actual melting, and a sharp demarcation between fused and unfused material was always observed.

Power was supplied from a 75-kva. transformer at 100 volts at an input which fluctuated between 40 and 80 kva. The average duration of the fusing operation was about 30 minutes. No effort was made to anneal the melt during cooling, and the entire bath probably solidified within 15 minutes after the removal of power.

Inasmuch as the two graphite electrodes were always in direct contact with the fused material, the melts were essentially reducing in character although carbon was added only to the mixes which contained natural olivine. Free iron, alloyed with indefinite proportions of silicon and minor metals, was produced in the olivine melts, but the magnesia-flint melts exhibited no visible metal. The experiments were conducted under natural pressure and exposed to the air.

Figure 3 shows the appearance of typical melt compositions. The discoloring effect of the high iron oxide content is shown in (*b*) and (*c*) of Fig. 3. Low MgO content is typified by a vitreous fracture with pronounced crystal development; high MgO compositions were characterized by a porous, bloated appearance; and compositions approaching forsterite (MgO 57.3%, SiO_2 42.7%) exhibited saccharoidal crystal development.

V. Density

Specific gravities were determined by the pycnometer method.[5] These data appear in Tables IV and V and in Fig. 4.

Figure 4 includes the density data taken from published literature (connected by straight lines) to show

[5] A.S.T.M. Serial Designation C135–38T, A.S.T.M. Book of Standards for 1939, Part II, pp. 968–69.

the relationship of theoretical and determined values as follows:

Material	Sp. gr.
Periclase	3.6*
Forsterite	3.216†
Clinoenstatite	3.28‡
Fused silica	2.21§

* E. S. Larsen and H. Berman, "Microscopic Determination of Nonopaque Minerals," *U. S. Geol. Survey Bull.*, No. 848 (2d ed.), p. 56 (1934); *Ceram. Abs.*, **13** [7] 196; [8] 221 (1934).

† *Ibid.*, p. 118.

‡ *Ibid.*, p. 119.

§ E. R. Berry, "Clear, Fused Quartz Made in Electric Furnace," *Trans. Electrochem. Soc.*, **45**, 511–21 (1924); p. 519.

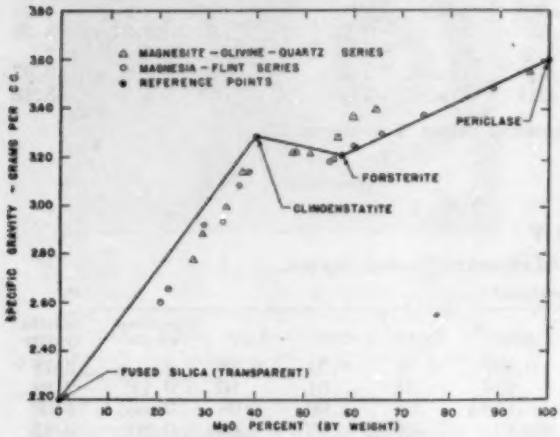

FIG. 4.—Specific gravity of melts.

Deviations from the theoretical values may be caused by foreign materials, such as silicates of metals other than magnesium, gas inclusions, glass, or ferrous alloys as well as by experimental errors in density determination and chemical analysis.

Actual density determinations were considerably lower than the theoretical curve for compositions up to 40% of MgO. The increasing proportions of glass in the higher silica compositions are probably responsible for the low densities observed.

Compositions above 40% of MgO yielded density values which agreed with the theoretical curves except for three specimens with unusually high density from the olivine series. Chemical analysis revealed that these specimens also had an unusually high iron content (Table V). Microscopic examination showed the iron to be present principally as minute metallic globules included within the crystals of forsterite. Calculated corrections based on this assumption brought the densities of these three specimens into excellent agreement with the theoretical curve of Fig. 4.

VI. Composition of Melts

Although the calculations of melt compositions (Tables II and III), based on typical raw material analyses (Table I), were not expected to agree with the final actual analyses, the trend represented by comparison of the data appears to be significant.

TABLE VI

COMPARISON OF CALCULATED AND ANALYZED FUSION COMPOSITIONS

Fusion No. (1)	MgO (%) (2)	MgO/SiO_2 ratios (A) Calculated (3)	MgO/SiO_2 ratios (B) Analyzed (4)	(A)/(B) (5)
		Olivine-magnesite-quartz series		
40-B	27.27	0.25	0.38	0.66
39-A	29.21	0.34	0.43	0.79
38-A	33.80	0.43	0.54	0.80
37-A	37.04	0.55	0.61	0.90
36-A	47.78	0.69	0.96	0.72
35-A	48.56	0.87	1.00	0.87
45-A	51.20	1.09	1.13	0.96
46-A*	56.85	1.33	1.48	0.90
47-A	59.50	1.65	1.75	0.94
48-A	64.38	2.00	2.22	0.90
55	96.35	93.1	90.8	1.03
		Magnesia-flint series		
60-R	20.53	0.24	0.27	0.89
61	22.38	0.29	0.30	0.97
62	29.82	0.37	0.44	0.84
63	33.24	0.42	0.50	0.84
64	36.61	0.46	0.59	0.76
65	38.71	0.52	0.64	0.81
66	55.41	1.04	1.29	0.81
16-A†	56.13	1.15	1.33	0.86
67	59.84	1.28	1.51	0.85
68	60.43	1.41	1.63	0.87
69	65.64	1.98	1.94	1.02
70	74.23	2.37	3.16	0.75
71	88.68	7.46	10.6	0.70

* Near forsterite composition.

† Approximate forsterite composition.

TABLE VII

PYROMETRIC CONE EQUIVALENTS

Sample No.	MgO (%)	P.C.E.	Sample No.	MgO (%)	P.C.E.
40-B	27.27	32	60-R	20.53	29–30
39-A	29.21	29	61	22.38	30–31
38-A	33.80	18–19	62	29.82	18–19
37-A	37.04	18–19	63	33.24	19
36-A	47.78	Uncertain	64	36.61	19
35-A	48.56	18–19	65	38.71	19
45-A	51.20	>37	66	55.41	>37
46-A	56.85	>37	67	59.84	>37
47-A	59.50	>37	68	60.43	>37
48-A	64.38	>37	69	65.64	>37
			70	74.23	>38
			71	88.68	>37

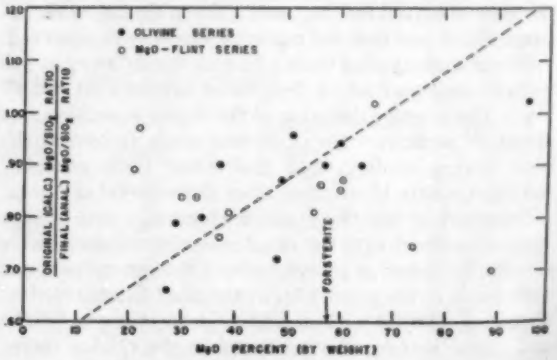

FIG. 5.—Magnesia-silica ratio plotted against melt composition.

Casual observation of the furnacing suggested at once that the copious evolution of white fumes certainly must be reflected in losses in one or both of the principal constituents. Silica and magnesia, in fact, are known to show appreciable vapor pressures at the temperatures involved. The MgO to SiO_2 ratio changes were therefore calculated to determine which constituent escapes more rapidly (Table VI).

Apparent differences were found in the arrangement of these data when the values from column (5) of Table VI were plotted against melt composition (see Fig. 5). The points of the olivine series, although scattered, indicate an extrapolated curve intersecting the unity ordinate at between 60 and 70% of MgO, which suggests that a composition higher in MgO would lose magnesia and result in silica enrichment of the melt. (Additional work is necessary to prove or disprove this assumption.)

The data of the magnesia-flint series, however, indicate random distribution of $(A)/(B)$ values in Fig. 5. The principal differences between the two series of charges were as follows: (1) Iron oxide was present in the olivine, (2) carbon was added to effect reduction of iron from the olivine, and (3) MgO and SiO_2 were already united in a strong molecular bond in olivine. The carbon, therefore, probably has also been responsible for the difference in rate of silica loss, either by direct reduction of SiO_2 or by the sweeping action of CO bubbling out of the melt and carrying off SiO_2 vapor (similar to steam distillation). If this assumption is correct, larger additions of carbon should increase this effect. From the limited evidence available, it is not possible to determine whether MgO-SiO_2 melts evaporate to provide fractional distillation or a minimum boiling mixture.

Other work* has shown that approximately 5% of silica in excess of magnesium-orthosilicate composition ($2MgO \cdot SiO_2$) may be eliminated during arc-furnace melting by the addition of carbon to the olivine charge fed to the furnace. (Larger excesses of silica, by inference, could be removed by continued or repeated furnacing operations.) The silica content, however, has never been carried below 42.7% ($2MgO \cdot SiO_2$) by reduction during any of the experimental melts conducted at Norris, even when large additions of carbon were charged.

The influence of temperature and impurities has not been considered up to this point. Variation in temperature, for example, will not necessarily produce proportional changes in the vapor pressures of specific materials, and melting temperatures of mixtures are profoundly influenced by changes in compositions. It is unlikely that any two of these fusions experienced identical thermal histories, and the observed discrepancies, therefore, are not unexpected.

VII. Pyrometric Cone Equivalent

Pyrometric cone equivalents were determined up to the maximum of the furnace, cone 37 (see Table VII). The P.C.E. for the high magnesia compositions, as expected, was beyond the capabilities of the furnace and presumably beyond the cone range. Pyrometric cone equivalent values could not be obtained on samples containing more than 51% of MgO, whereas samples containing 29.8 to 49% of MgO yielded values of cones 18 to 19. This low-temperature plateau has been explained only by assuming the presence of a low-melting eutectic composition throughout this range. The temperatures represented by cones 18 to 19 are lower than the minimum eutectic melting point indicated by the phase diagram (see Fig. 1).

VIII. Mineralogical Examinations

To interpret the results obtained from the furnace work, microscopic-petrographic, chemical, and spectrographic studies were made, and the data are presented in tabular form where possible. Megascopic observations on "hand specimens" are presented in Table VIII. The two columns permit direct comparison of color, texture, and structure of the related charges in the two series. Color is a rough index of purity.

The petrographic studies are presented as brief descriptions of the samples, each based on one thin section. When the forsterite crystals are coarse as in No. 36-A, the sampling error is quite large. The chemical and synthesis data are consistent for the other charges.

IX. Petrographic Examinations

(1) Magnesia-Flint Series

(For compositions, see Table IV.)

No. 71: Thin section, granitic texture of anhedral grains of periclase (MgO) with interstitial forsterite or, more rarely, forsterite grains (Fig. 6(*a*)); refractive index of periclase, $n = 1.735 \pm 0.002$; same value for pure periclase.

No. 70: Thin section, texture distinctly poikilitic; equidimensional periclase crystals quite uniformly distributed in large forsterite host crystals (Fig. 6(*b*)); forsterite optical properties,

$\alpha = 1.635$; $\beta = 1.650$; $\gamma = 1.669$; all ± 0.002; biaxial (+); $2V = 84°$ (graphically determined); $\gamma - \alpha = 0.034$.

Properties agree with those given by Bowen and Schairer[3] for pure forsterite,

$\alpha = 1.6359$; $\beta = 1.6507$; $\gamma = 1.6688$; biaxial (+); $\gamma - \alpha = 0.0329$.

No. 17: Globular periclase grains poikilitically inclosed within forsterite host crystals (Fig. 6(*c*)); about $\pm 65\%$ of forsterite and $\pm 35\%$ of periclase; spectrographic analysis shows magnesium and silicon as main metallic elements; aluminum only in small quantity; traces of iron, sodium, calcium, vanadium, and chromium.

No. 69: Poikilitic texture, forsterite crystals quite large (Fig. 6(*d*)).

No. 68: Poikilitic texture (Fig. 7(*a*)).

No. 67: Poikilitic texture; periclase grains rarer (Fig. 7(*b*)).

No. 16-A: Thin section, coarse texture of prismatic crystals of forsterite with subhedral to anhedral

* Unpublished data.

TABLE VIII

MEGASCOPIC DESCRIPTION OF MELTS

Magnesia-flint series				Olivine-magnesite-quartz series			
	Composition by analysis				Composition by analysis		
No.	MgO	SiO_2	Remarks	No.	MgO	SiO_2	Remarks
				55	96.4	1.6	Dense crystalline greenish-tinted mass; myriad of tiny crystals reflects light as specimen is rotated
71	88.7	8.2	White, dense, finely crystalline (saccharoidal) masses				
70	74.2	23.5	Gray, dense crystalline masses; occasional lenses of white porous material; somewhat vitreous in luster				
17	67.6	31.4	Gray, densely crystalline				
69	65.6	33.8	Light gray, vitreous crystals of olivine; porous lumps	48-A	64.4	29.0	Dark greenish brown crystalline masses; quite porous; slaglike
68	60.4	37.0	Grayish olivine crystals	47-A	59.5	34.0	Dark greenish brown crystalline lumps
67	59.8	39.7	Grayish crystalline olivine				
16-A	56.1	42.2	Colorless, granular olivine crystals; open structure	46-A	56.9	38.2	Grayish green granular olivine; structure quite porous
66	55.4	42.9	Colorless to white, dense, coarsely crystalline aggregates of olivine; prismatic crystals	45-A	51.2	45.5	Grayish saccharoidal masses; crystals stubby; structure quite open; some white clinoenstatite
				35-A	48.6	48.7	Gray, crystalline masses of stubby olivine and some white clinoenstatite laths
				36-A	47.8	49.7	Saccharoidal olivine crystals; stubby vitreous olivine crystals in cavities; matrix, vitreous olivine with white clinoenstatite filling around grains
65	38.7	60.7	Grayish masses, lath-shaped divergent clinoenstatite crystals; glass coats surfaces				
64	36.6	62.4	Grayish white (darker than No. 63); radiating laths of clinoenstatite; laths shorter than No. 63	37-A	37.0	61.1	Grayish white, radiating laths of clinoenstatite; cavities becoming smaller; ferrosilicon in small amounts
63	33.2	66.1	White, divergent crystalline masses; clinoenstatite crystals, skeletal and box-shaped; often only part of box-work present, giving rise to L-shaped appearance	38-A	33.8	62.2	Grayish white, divergent radiating structure; cavities quite large and lined with lath-shaped crystals oriented parallel to cavity walls; some glass easily recognized; cavities may show reddish cast
62	29.8	68.2	Grayish white; radiating structure emphasized by tubular cavities parallel to lengths of laths; a little glass present	39-A	29.2	67.4	Grayish white, radiating fibers; pearly luster in cavities; grayish glass and ferrosilicon present
				40-B	27.3	70.9	Grayish white, dense, porcelanous masses, with vugs; walls of vugs usually lath-shaped crystals parallel to wall structure; yellow glass blebs and ferrosilicon
61	22.4	75.6	Dense gray fibers or laths, prominent divergent radiating structure; blebs of yellow glass; some white material				
60	20.5	77.1	Dense grayish, porcelanous masses with yellow blebs of glass; radiating fibers in some areas				

forsterite grains in interstices (Fig. 7(*c*)); occasional mosaic patches of small forsterite crystals; parallel cavities, with some definite orientation of entire cavity system within crystals; cavities (probably from contraction on cooling) frequently sheetlike; thickness only small fraction of length, some shift direction near terminus (rarely arranged as herringbones); minor quantities of low refractive index glass; forsterite optical properties,

$\alpha = 1.634$; $\beta = 1.649$; $\gamma = 1.668$; all ± 0.002; biaxial (+); $\gamma - \alpha = 0.034$; $2V = 82°$ (determined graphically); $\rho < \nu$.

Spectroscopic analysis: Main constituents, Mg, Si; small amount, Al; trace, Fe, Na, Ca.

No. 66: Thin section, coarse-grained, prismatic olivine crystals with interstitial clinoenstatite (Fig. 7(*d*)); latter segregated in bundles in interstices with occasional filling along cracks; clinoenstatite, length-

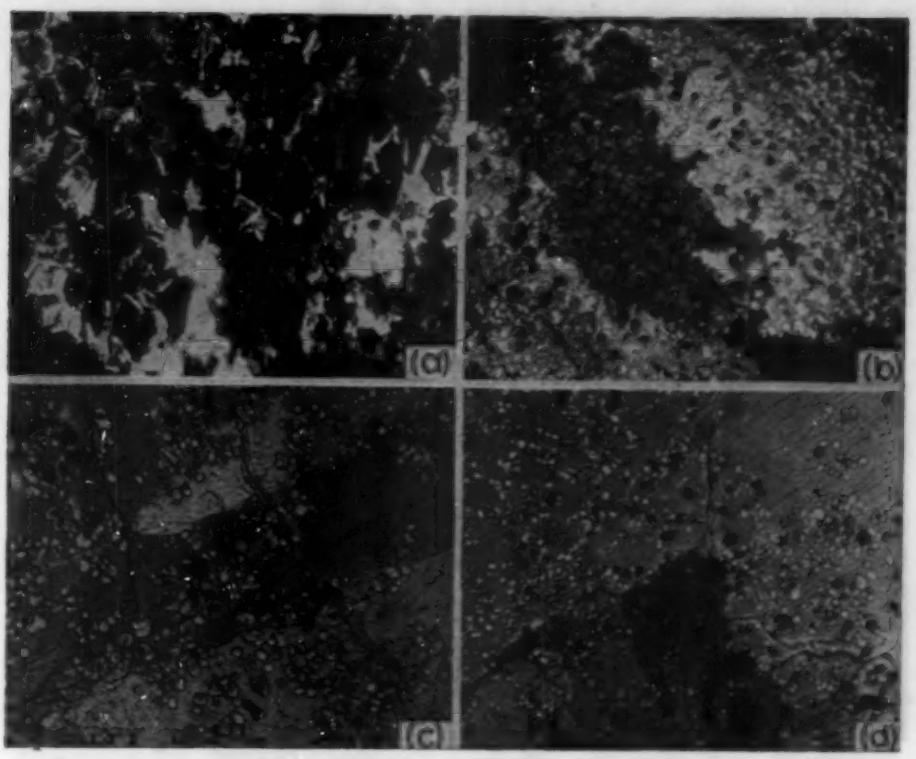

FIG. 6.—(*a*) *Melt No. 71:* MgO 88.7% and SiO_2 8.2%; dark areas, periclase grains outlined by light or dark boundaries; bright areas, interstitial forsterite films and grains; polarized light, ×50.
(*b*) *Melt No. 70:* MgO 74.2% and SiO_2 23.5%; large forsterite grains contain periclase inclusions; MgO grain size distinctly smaller than in Fig. 6 (*a*); polarized light, ×50.
(*c*) *Melt No. 17:* MgO 67.6% and SiO_2 31.4%; large forsterite grains contain periclase inclusions; polarized light, ×50.
(*d*) *Melt No. 69:* MgO 65.6% and SiO_2 33.8%; periclase inclusions in forsterite; polarized light, ×50.

slow, about 1 or 2% in thin section; some glass in cracks with refractive index above that of balsam but much below forsterite.

No. 15: Forsterite (present as anhedra and subhedra) dominant mineral, about ≐70% of thin section (Fig. 8(*a*)); remainder, divergent clinoenstatite laths of low double refraction, polysynthetically twinned on very fine scale; about 0.5% of opaque grains; chemical analysis of bulk sample (E. E. Creitz, analyst) as follows:

	(%)
SiO_2	48.20
Al_2O_3	0.59
FeO	0.26
MgO	51.60
	100.65

Spectrographic analysis: Main elements, Mg, Si; small amount, Al; trace, Fe, Ca, Na.

No. 65: Clinoenstatite as radiating laths, length-slow (Fig. 8(*b*)); when cut across length, laths give rise to skeletal prismatic cross section, about 10% of thin slice; polysynthetic twinning on exceedingly fine scale discernible (at high magnifications); very small quantity of glass with refractive index just above that of balsam; when reheated for 4½ hr. to ≐1500°C., well-developed clinoenstatite (shows very fine polysynthetic twinning) and traces of glass.

$$\gamma_{Na} = 1.661 \pm 0.002;\ \alpha_{Na} = 1.651 \pm 0.002.$$

No. 64: Two types of divergent laths (Fig. 8(*c*)); type (1) laths, large blades of myriad thin twin lamellae continuous for short distances in lath, twin lamellae broken by tiny cracks perpendicular to length, extinction may be continuous over number of these cracks, then shifts, twinning lamellae appear near extinction position; type (2) laths, clinoenstatite microlites in glass, brownish, which appear to have formed in interstices between first type.

No. 63: Thin section, (*a*) parallel and (*b*) intersecting laths (Fig. 8(*d*)); (*a*) type, grayish, blades of clinoenstatite with polysynthetic twinning lamellae visible at high magnifications; (*b*) type, brownish, bladelike structures appear to fill interstices between type (*a*) blades; type (*b*) laths made up of microlites in glass, sort of plumose structure perpendicular to length of lath, probably result of shrinkage of glass during cooling;

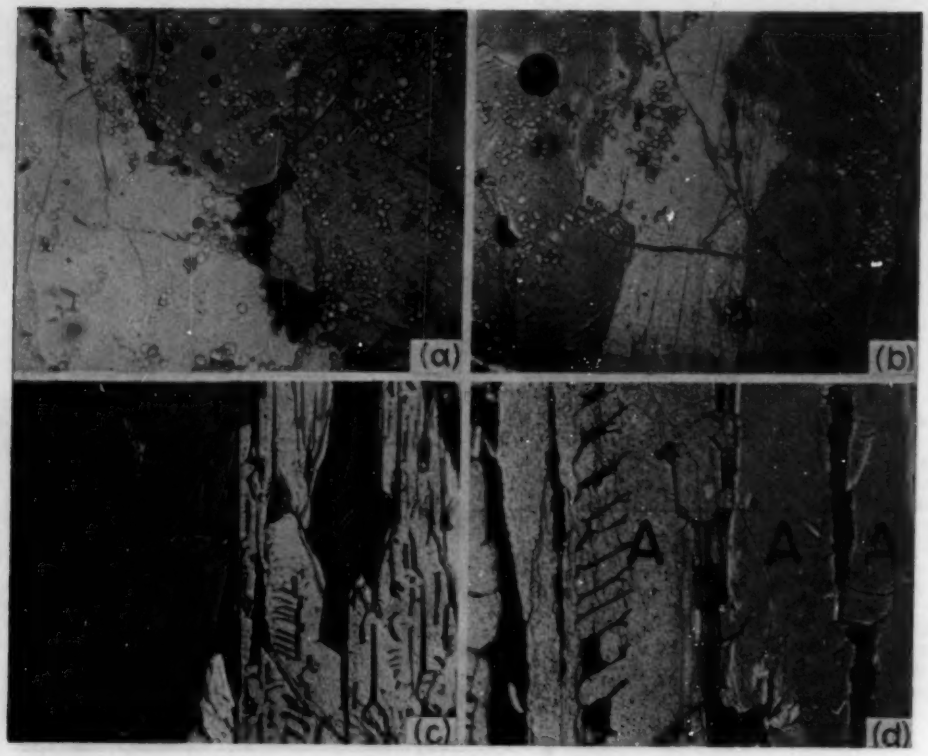

FIG. 7 (see legend on opposite page).

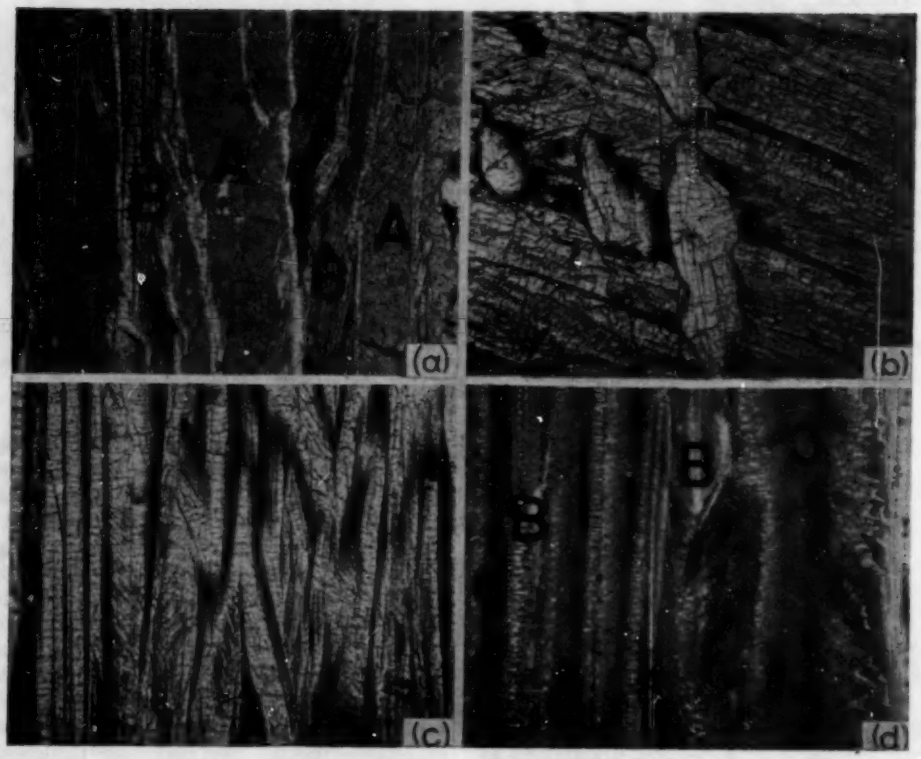

FIG. 8 (see legend on opposite page).

FIG. 7.—(*a*) *Melt No. 68:* MgO 60.4% and SiO_2 37.0%; small periclase inclusions in forsterite grains; large black areas, voids; polarized light, ×50.
(*b*) *Melt No. 67:* MgO 59.8% and SiO_2 39.7%; few remaining periclase grains in forsterite hosts; polarized light, ×50.
(*c*) *Melt No. 16-A:* MgO 56.1% and SiO_2 42.2%; forsterite grains contain parallel cavities, no periclase or clinoenstatite; long dark area, forsterite grain near extinction position; smaller dark areas, voids and cavities; theoretical forsterite composition, MgO 57.3% and SiO_2 42.7%; traces of glass in cavities; polarized light, ×50.
(*d*) *Melt No. 66:* MgO 55.4% and SiO_2 42.9%; large forsterite grains, *A*, with interstitial bundle of fibrous clinoenstatite, *B;* dark areas, cavities or voids; polarized light, ×50.

FIG. 8.—(*a*) *Melt No. 15:* MgO 51.6% and SiO_2 48.2%; interstitial clinoenstatite, *B*, between forsterite grains, *A;* note cracks perpendicular to length of clinoenstatite laths; polarized light, ×50.
(*b*) *Melt No. 65:* MgO 38.7% and SiO_2 60.7%; entire section comprises clinoenstatite grains exhibiting cracks diagonal as well as perpendicular to length; polarized light, ×50.
(*c*) *Melt No. 64:* MgO 36.6% and SiO_2 62.4%; divergent laths of clinoenstatite (light blades) with interstitial glass containing microlites (darker fibrous areas); both appear light although minuteness of microlites does not permit optical measurements; polarized light, ×50.
(*d*) *Melt No. 63:* MgO 33.2% and SiO_2 66.1%; clinoenstatite laths, *B*, with interstitial glass, *C*, containing microlites; polarized light, ×50.

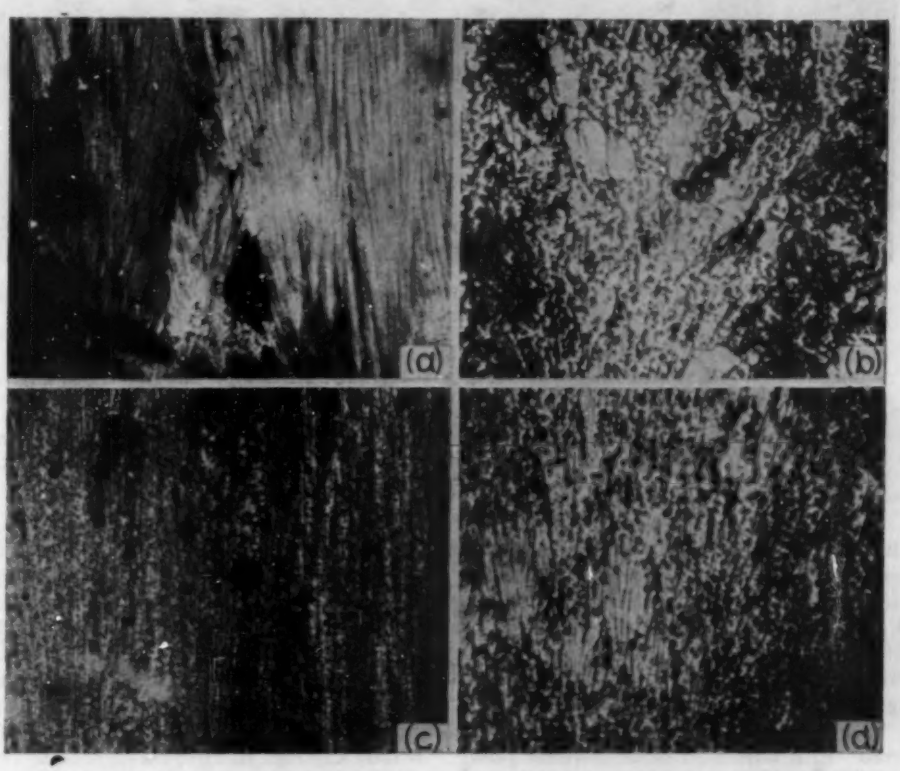

FIG. 9.—(*a*) *Melt No. 62:* MgO 29.8% and SiO_2 68.2%; short divergent laths principally microlite-filled glass; black areas, voids; lightest spots, clinoenstatite crystal nuclei; globules of immiscible phase indistinctly visible; polarized light, ×50.
(*b*) *Melt No. 62:* After reheating 4.5 hr. at 1500°C.; section, well-developed clinoenstatite (light), glass (dark), and rare cristobalite; polarized light, ×50.
(*c*) *Melt No. 61:* MgO 22.4% and SiO_2 75.6%; divergent development of clinoenstatite microlites in glassy phase; note small spheres of immiscible silicate phase persist in solidified melt; polarized light, ×50.
(*d*) *Melt No. 61:* After reheating 4.5 hr. at 1500°C.; well-developed clinoenstatite crystals with spheres of immiscible phase persisting; polarized light, ×50.

constant structural character probably consequent on anisotropy of heat conduction of clinoenstatite laths; occasional skeletal crystals, showing prismatic cross section, disturb continuity of laths.

No. 62: Fragmentary thin section, brownish divergent laths (Fig. 9(*a*)) shorter than previous specimens; section almost opaque at low magnifications except for occasional irregular patches of coarse, gray clinoen-

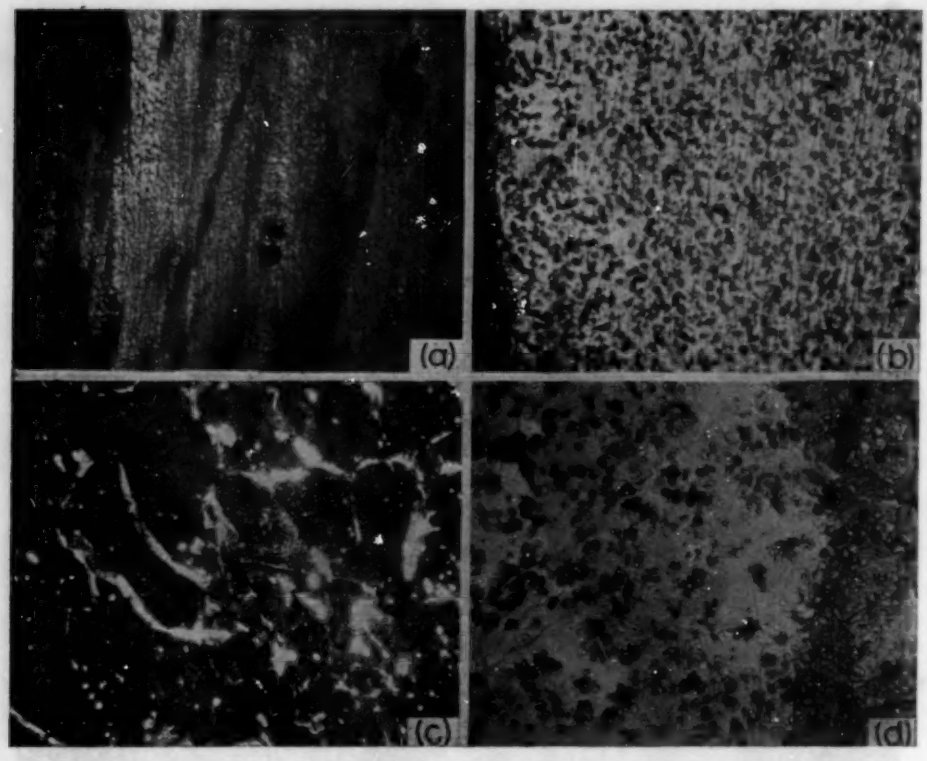

FIG. 10.—(*a*) *Melt No. 60-R:* MgO 20.5% and SiO_2 77.1%; minute immiscible glass spheres, inclusions in divergent laths, also clinoenstatite microlites; polarized light, ×50.
(*b*) *Melt No. 60-R:* After reheating 4.5 hr. at 1500°C.; clinoenstatite crystals, well-developed, immiscible spheres of glass, black dots; polarized light, ×50.
(*c*) *Melt No. 55 (Fused Magnesite):* MgO 96.4% and SiO_2 1.6%; large periclase grains outlined by black and white boundary lines; white lines, interstitial films of forsterite; polarized light, ×50.
(*d*) *Melt No. 48-A:* MgO 64.4% and SiO_2 29.0%; poikilitic magnesio-wüstite inclusions in forsterite hosts; many arboreal included grains; black dots, larger MgO particles whose top and bottom faces were cut in polishing section; polarized light, ×50.

statite; thin section pocked with holes which may contain glass; in one cavity, glass index of refraction greater than balsam; birefringence of section very low (considered as whole) and interference colors almost anomalous; charge consists of clinoenstatite, glass, and rare cristobalite when heated to ±1500°C. for 4½ hr. (Fig. 9 (*b*)).

No. 61: Thin section, finely divergent laths, literally "peppered" with numerous small globular glassy bodies (Fig. 9 (*c*)); laths length-slow; occasional patch of clinoenstatite shows through slice, resembling knotlike patch in wood; laths of fine clinoenstatite microlites in glassy phase; immiscible globules of isotropic glass; index of refraction less than Canada balsam; same charge, well-developed clinoenstatite laths when reheated for 4½ hr. to ±1500°C. (Fig. 9 (*d*)); shadowy extinction, 18.5-degree angle on one grain (not maximum value); square areas also present with low but detectable birefringence; refractive index for one ray, $n = 1.487$; other ray slightly lower; this phase, cristobalite (another sample examined by T. N. McVay showed glass instead of cristobalite; such inequilibrium not entirely unexpected in charges so rich in silica).

No. 60-R: Immiscible glass phase abundant as globules (Fig. 10 (*a*)); refractive index very low; divergent laths length-slow; appear to consist of microlites of clinoenstatite in glassy phase of higher refractive index than globular blebs; globular glass phase considerably below 1.540; other glass phase appears to be above 1.540; same charge, clinoenstatite developed into well-defined laths when reheated 4½ hr. to ±1500°C. (Fig. 10 (*b*)); polysynthetic twinning quite fine, gives rise to shadowy extinction; indices of refraction,

$$\alpha' = 1.652;\ \gamma' = 1.661.$$

Owing to fine character of twinning, exact extinction angle not measurable; low-refractive index glassy material present.

(2) Olivine-Magnesite-Quartz Series

(For compositions, see Table V.)

No. 55: 100% calcined magnesite, texture distinctly granitic with magnesio-wüstite (solid solutions of FeO and MgO) as anhedral grains (Fig. 10 (*c*)); some grains polygonal; forsterite usually occurs as rims about

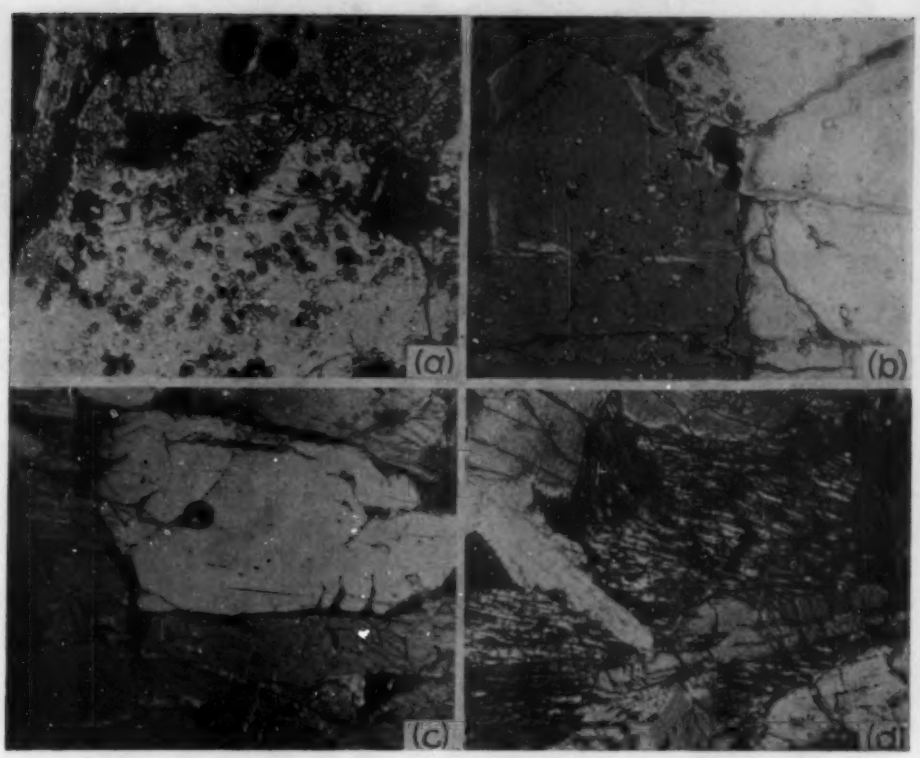

FIG. 11.—(*a*) *Melt No. 47-A:* MgO 59.5% and SiO_2 34.0%; magnesio-wüstite grains from deep brown to colorless in two large forsterite grains; large black areas, voids in section; polarized light, ×50.
(*b*) *Melt No. 46-A:* MgO 56.9% and SiO_2 38.3%; few magnesio-wüstite anhedra poikilitically inclosed in large forsterite grains; arboreal development noticeable; polarized light, ×50.
(*c*) *Melt No. 45-A:* MgO 51.2% and SiO_2 45.5%; forsterite grains surrounded by interstitial, fibrous clinoenstatite; spherule of ferrosilicon in light-colored central crystal; polarized light, ×50.
(*d*) *Melt No. 35-A:* MgO 48.6% and SiO_2 48.7%; subhedral, fibrous bundles of clinoenstatite appear as large patches; interstitial developments outline forsterite grains; polarized light, ×50.

magnesio-wüstite grains, interstitial filling, or lenses in cleavage cracks; anhedra of magnesio-wüstite, pale gray; refractive index measured on some grains, $n_{Na} = 1.741 \pm 0.003$, indicating slight but detectable solid solution of wüstite in periclase.

No. 48-A: Section, granular forsterite with poikiliticaliy included magnesio-wüstite (Fig. 10 (*d*)); some opaque material; β index of refraction for forsterite, 1.652, compares favorably with 1.651 of pure Mg_2SiO_4; magnesio-wüstite anhedra almost colorless to deep brown; refractive index of deepest brown grains (in one sample) 1.770, corresponding to FeO content of about 10% by weight; refractive index for grains of lighter shades correspondingly less.

No. 47-A: Melt similar to *No. 48-A* except granular forsterite contains smaller quantity of poikilitic magnesio-wüstite from almost colorless to deep brown (Fig. 11 (*a*)).

No. 46-A: Section, granular forsterite with magnesio-wüstite anhedra diminishing in size and amount, deep brown to colorless (Fig. 11 (*b*)); optical properties of forsterite,

$\alpha = 1.635$; $\beta = 1.650$; $\gamma = 1.669$; all ± 0.003; biaxial (+); 2V = 82° (graphically determined); $\gamma - \alpha = 0.034$.

No. 45-A: Forsterite coarsely crystalline, attaining maximum 3-mm. length; anhedral and euhedral crystals; forsterite about 95% of thin section (Fig. 11 (*c*)); euhedral forsterite resembles typical olivine in igneous rocks, traces of (101) and (010) or (100), (110), and (010) planes; clinoenstatite, about 5% of area, fills interstices and emphasizes forsterite outline; β index of refraction measured in sodium light, 1.653 ± 0.002; higher than values for pure forsterite; represents solid solution with small but detectable amount of fayalite; careful examination of hand specimen discloses tiny spherules of magnetic iron alloy, which accounts for most of iron oxide in analysis.

No. 35-A: Forsterite, 70% of section by area; stubby subhedral crystals; one crystal 2-mm. long; average size about 1 mm.; clinoenstatite, principally radiating fibers in interstices or feathery needles parallel to forsterite grains or cutting through grains (Fig. 11 (*d*)); occasional large areas of clinoenstatite;

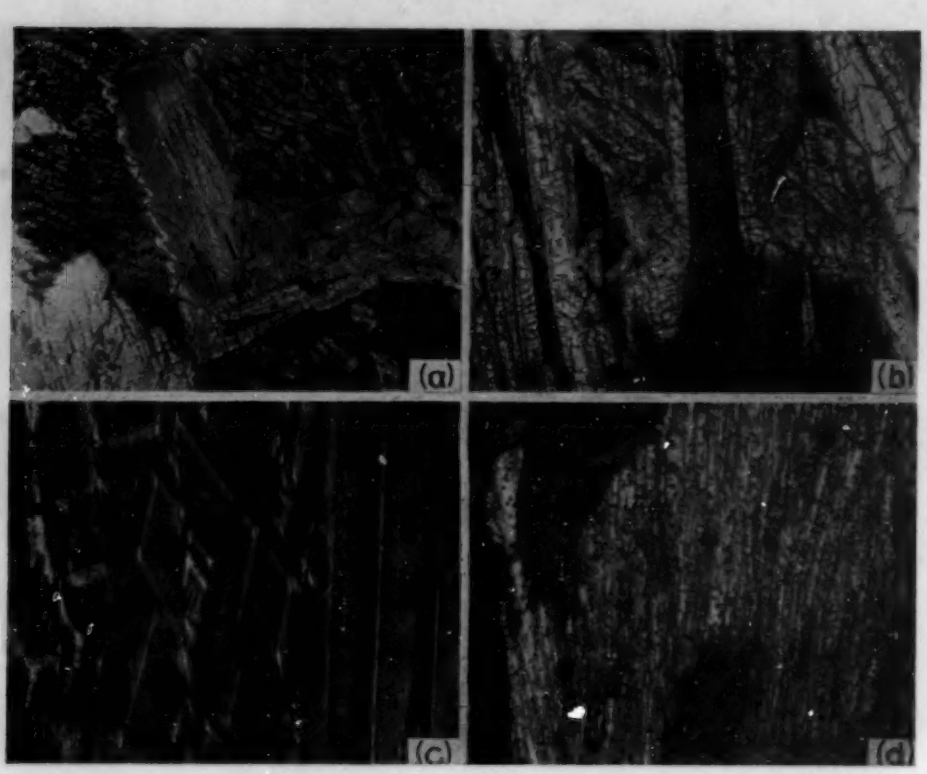

FIG. 12.—(*a*) *Melt No. 36-A:* MgO 47.8% and SiO_2 49.7%; U-shaped, skeletal forsterite crystal completely embedded in clinoenstatite; even the three walls of large crystal filled with fibrous clinoenstatite; polarized light, ×50.
(*b*) *Melt No. 37-A:* MgO 37.0% and SiO_2 61.1%; most of section, well-developed clinoenstatite; polarized light, ×50.
(*c*) *Melt No. 38-A:* MgO 33.8% and SiO_2 62.2%; skeletal, prismatic sections as well as blades of clinoenstatite; brownish glass containing microlites, dark streaks; polarized light, ×50.
(*d*) *Melt No. 39-A:* MgO 29.2% and SiO_2 67.4%; divergent laths, microlites of clinoenstatite in brownish glass; minute spherules of immiscible glass poikilitically inclosed, uniformly distributed; polarized light, ×50.

boxwork of skeletal clinoenstatite crystals forms striking patch throughout section; β index for forsterite measured in sodium light, 1.653 ± 0.002; tiny spherules of iron alloy, readily discernible in hand specimen under hand lens, account for relatively high percentage of iron oxide in analysis.

No. 36-A: Forsterite still dominant constituent in thin section; crystals, stubby and subhedral, exhibit much evidence of resorption to form clinoenstatite (as expected from phase-rule relations for this system); corrosion of forsterite along borders or crevices; fragments originally belonging to same crystal sometimes isolated as islands in clinoenstatite base; separate fragments may still extinguish as unit; one forsterite crystal, narrow shell with interior entirely replaced by clinoenstatite (Fig. 12 (*a*)); maximum length of forsterite 1.2 mm., average length much less; maximum length of clinoenstatite laths, 0.6 mm.; skeletal boxwork of clinoenstatite present; β index of forsterite measured in sodium light, 1.652 ± 0.002.

No. 37-A: Bulk of section, well-crystallized clinoenstatite laths (Fig. 12 (*b*)); coarse crystallization, polysynthetic twinning easily discernible; maximum extinction angle 16 degrees (accuracy of measurement unknown owing to character of twinning); wedge-shaped crystals noted as acute rhombic cross section of clinoenstatite prisms; brownish glassy substance with microlites only small percentage of section; index of glass less than Canada balsam.

No. 38-A: Thin section, distinctly brownish, coarse blades of clinoenstatite, length-slow, and brownish interstitial glass; wedge-shaped, prismatic sections of skeletal clinoenstatite occasionally break through blades (Fig. 12 (*c*)); featherlike structure in clinoenstatite laths normal to length of lath (believed due to anisotropy in heat conduction of laths) causes cooled glass to shrink to constant and characteristic structure; refractive index of glass less than balsam.

No. 39-A: Chief phases, divergent brownish laths apparently clinoenstatite microlites in glass, oriented in parallel fashion (Fig. 12 (*d*)); laths "peppered" with tiny globules of immiscible phase poikilitically inclosed; some interstitial laths almost isotropic but contain microlites; all laths, length-slow; some laths show

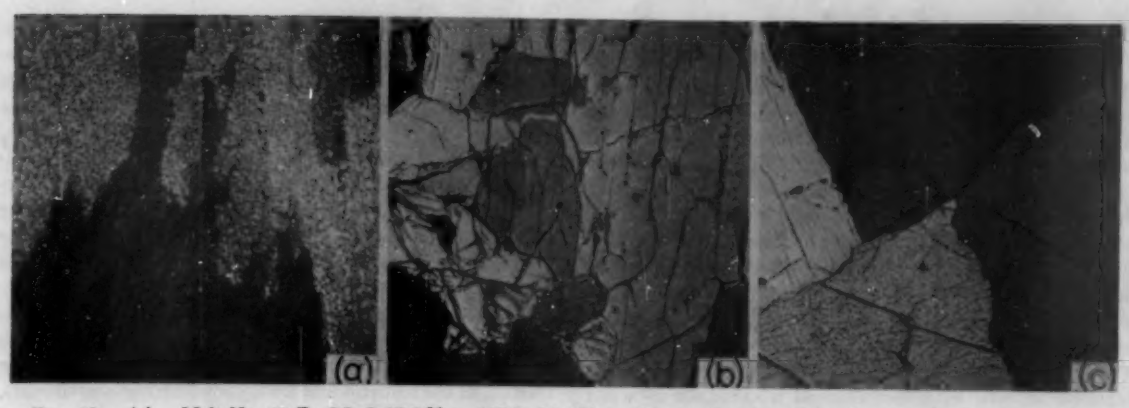

FIG. 13.—(*a*) *Melt No. 40-B:* MgO 27.3% and SiO_2 70.9%; oriented clinoenstatite microlites in divergent brownish laths; minute, immiscible, glass spheres poikilitically inclosed; polarized light, ×50.
(*b*) *Olivine Melt No. 9:* Forsterite grains from olivine; no periclase or clinoenstatite, traces of glass; polarized light, ×50.
(*c*) *Olivine Melt No. 14:* Mosaic pattern of anhedral forsterite grains without observable glass, clinoenstatite, or periclase; polarized light, ×50.

separation; feathery structure, mentioned previously, common to all; refractive index of immiscible glassy phase well below balsam.

No. 40-B: Clinoenstatite microlites in divergent brownish laths, length-slow (Fig. 13 (*a*)); laths "peppered" with immiscible glass phase, poikilitically inclosed; from presence of so much glass (both large and small blebs, poikilitically inclosed), clinoenstatite seems to have strong crystallizing power.

A comparison-microscope study, made at low magnifications, of the grain size and texture of analogous products in the two series is given in Table IX.

TABLE IX

COMPARISON-MICROSCOPE STUDY OF GRAIN SIZE AND TEXTURE OF ANALOGOUS PRODUCTS IN TWO SERIES

Magnesia-flint series	Olivine-magnesite-quartz series
No. 69	No. 48-A
Grains of forsterite about same size in both products	
No. 17	No. 47-A
Periclase larger in No. 17 than magnesio-wüstite in No. 47-A; forsterite grains about same in both slides	
No. 67	No. 46-A
Forsterite grains, prismatic	Forsterite grains, stubby
No. 66	No. 35-A
Coarse prismatic forsterite crystals	Stubby forsterite crystals, euhedral to subhedral
No. 65	No. 37-A
Divergent laths and fibrous crystals	Divergent laths much wider than No. 65
No. 62	No. 38-A
Exceedingly narrow fibers	Laths to blades, also skeletal clinoenstatite
No. 61	No. 39-A
Blades in No. 61 narrower and blebs slightly larger than No. 39-A	
No. 60	No. 40-B
Exceedingly narrow blades	Blades narrower and blebs seem larger than in No. 60

Micrometric surveys were made on all sections in the system forsterite–periclase inasmuch as they were particularly suited to such measurements. The improved Wentworth recording micrometer described by Hunt[6] was used for the measurements. A 10 × objective and a 10 × ocular were employed, giving a magnification of 100 diameters. The gypsum plate was of particular value in identification owing to the isotropic character of the periclase. The results are given in Tables X and XI.

[6] W. F. Hunt, "Improved Wentworth Recording Micrometer," *Amer. Mineralogist*, 9, 190–94 (1924).

TABLE X

MICROMETRIC ANALYSES OF SYSTEM FORSTERITE–PERICLASE (MAGNESIA-FLINT SERIES)

Thin section No. (1)	No. of traverses (2)	Periclase: No. of grains (3)	Periclase: Avg. size (μ) (4)	Periclase: Weight (%) (5)	Forsterite weight (%) (6)
71	15	1995	65	75.9	24.1
70	15	3415	30	65.6	34.4
17	10			36.7	63.3
69	10	1681	21	34.6	65.4
68	10	1055	19	22.5	77.5
67	10	587	18	11.7	88.3
16-A				00.0	100.0

TABLE XI

MICROMETRIC ANALYSES OF OLIVINE-MAGNESITE-QUARTZ SERIES

Thin section No. (1)	No. of traverses (2)	Magnesio-wüstite: No. of grains (3)	Magnesio-wüstite: Avg. size (μ) (4)	Magnesio-wüstite: Weight (%) (5)	Forsterite weight (%) (6)
55	10	559	172	94.7	5.3
48-A	10	940	24	34.5	65.5
47-A	10	522	21	21.4	78.6
46-A	10	234	24.6	7.0	93.0

(3) Grain Size of Periclase and Magnesio-Wüstite

A cursory examination of the thin sections showed that the average grain size[7] of the periclase and magnesio-wüstite varied with its abundance. The number of grains of periclase was therefore recorded on hand counters when the micrometric analyses were made. Using this value and the total distance of the periclase traversed, the average size of the crystals was calculated. The grains with few exceptions are rounded and appear to lie between a sphere and an octahedron in shape. Some bleblike structures were observed which tended toward arborescence. These data are given in column (4) of Tables X and XI, and to emphasize this relationship, they are also presented in Fig. 14. This decrease in size with decrease in abundance is what might be expected.

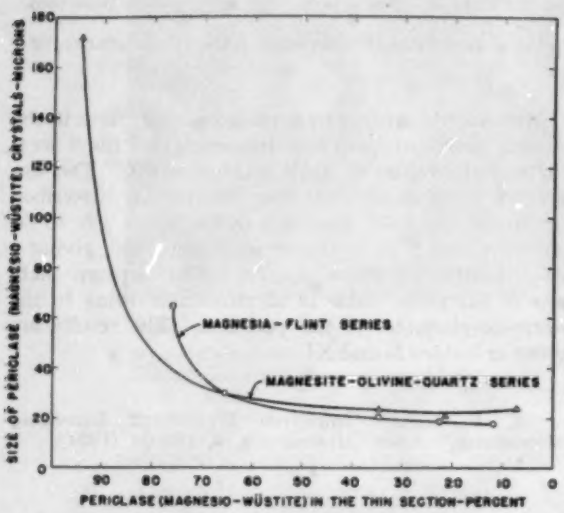

FIG. 14.—Size of periclase (magnesio-wüstite) grains as function of composition in system MgO–Mg_2SiO_4.

An interesting series of observations on periclas crystals in refractories is recorded by Andersen. For dead-burned magnesites, he states

> The periclase occurs as rounded or indistinctly polygonal grains of a fairly uniform size, by far the greater part measuring between 0.02 and 0.04 millimeter in diameter.....
>
> The structure of the dead-burned magnesia seems to be little influenced by the structure of the crude magnesite rock from which it is made or by the size of the fragments of the crushed rock as shown by the following facts: Samples of the crude magnesite vary considerably in structure; especially does the grain size vary from one sample to another or even from place to place within one little sample. In spite of these variations in the crude rock, numerous samples of the dead-burned magnesia examined under the microscope all show practically the same structure (grain size and fabric of the aggregates). The aggregates of periclase in the dead-burned magnesia are always much more fine grained than the aggregates of magnesite in the crude rock; in other words, each individual of magnesite gives rise to a number of individuals of periclase. The size of the periclase grains is evidently determined by the influence of the fluxes formed during the dead-burning and not by the size of the original magnesite grains or by the size of the composite particles of the crushed rock.
>
> When such a rock (magnesite) is heated to the temperature of dead-burning, i.e., to a temperature high enough for the complete decomposition of the carbonates and the melting of the silicates and iron oxide-bearing constituents, it will form a crystallized aggregate consisting largely of grains of periclase (crystallized MgO).....

On the basis of their extensive study of magnesite refractories, Fisk and McCaughey[9] in addition found that

> In these refractories composed of periclase, the latter is generally present in the form of rounded pealike bodies of microscopic dimensions (0.1 mm. or less)..... These periclase grains do not seem to have the ability to develop much larger particles and form more coarsely crystalline structures. This habit of forming aggregates of rounded periclase grains instead of large interlocking crystals is peculiar to high magnesia refractories as matured in steel furnaces. This type of structure required the presence of an auxiliary bond, and generally the structure is one of periclase grains cemented by a silicate either of calcium or magnesium. The periclase has a limited solution range in these silicate bonds at the temperatures involved.

Fisk and McCaughey also include a photomicrograph of a thin section of an open-hearth furnace bottom to illustrate their observations.

Fettke[10] found that a magnesite brick made of Washington (U.S.A.) magnesite rock had developed periclase crystals of 0.05-mm. (50 μ) average diameter, whereas a brick made from Austrian magnesite developed periclase ranging from 0.08 mm. (80 μ) on down in size.

For systems that involve crystallization of periclase out of melts containing olivine, it thus appears that a phenomenon operates to form numerous nuclei, which grow more or less to the same size and give rise to an even-grained rather than to a porphyritic texture. This does not mean that periclase will not grow to form large crystals in other systems. Larger crystals have been reported. The curve in Fig. 14 also indicates that the size of the crystals of periclase increases rapidly as the melts approach pure MgO.

---

[7] W. C. Krumbein, "Thin-Section Mechanical Analysis of Indurated Sediments," *Jour. Geol.*, **43** [5] 482–96 (July–August, 1935).

[8] Olaf Andersen, "Magnesia Refractories in Basic Open-Hearth Steel Furnaces," *Jour. Amer. Ceram. Soc.*, **17** [8] 221–35 (1934).

[9] H. G. Fisk and W. J. McCaughey, "Equilibrium Studies in Systems Containing Magnesium Oxide, Iron Oxide, and Magnesium Aluminate," Ohio State Univ. Studies, Engineering Series, Vol. I, No. 4, Part I; *Bull.*, No. 70, p. 3 (July, 1932); *Ceram. Abs.*, **12** [3] 128 (1933).

[10] C. R. Fettke cited by J. S. McDowell and R. M. Howe in "Magnesite Refractories," *Jour. Amer. Ceram. Soc.*, **3** [3] 185–246 (1920); pp. 232–33.

(4) Natural Olivines Improved by Electrical Fusion

In the course of the experiments, numerous fusions of natural olivine were made to determine the character of the product that could be produced by an electric furnace. Three such trials are presented in Table XII. Iron has definitely been reduced to a very small quantity, ranging from 0.11 to 0.68% of FeO, some of which is contributed by ferrosilicon. This reduction of iron is a decided improvement over the natural olivine, which contains 8.0% of iron oxide (calculated as Fe_2O_3). If the other minor oxides (namely, the moisture and alumina and titania) are disregarded and all of the iron is considered to be present in the ferrous state, the natural olivine would contain 7.2% of FeO, equivalent roughly to 10.2% of fayalite.

According to the phase relations of the olivine solid solutions as depicted by Bowen and Schairer,[3] if natural olivine of uniform composition and containing roughly 10.2% by weight of the fayalite molecule is heated, it will develop a liquid phase at approximately 1770°C. The improved olivines, as prepared in the electric furnace and containing at most 1% by weight of the fayalite molecule, would develop the first trace of its liquid phase at approximately 1870°C. This difference of about 100°C. is particularly important at such high temperatures when the olivine is destined for refractory manufacture.

(5) Effect of Various Impurities on Optical Properties

There are two sets of data in the magnesia-flint series from which to determine the quantity of impurities in the samples. The analyses of the end members (flint and magnesium carbonate) show that alumina, iron oxides, and alkalis are the only constituents present in noteworthy amounts. Spectrographic analyses were made on three fired charges of the following compositions: MgO 50% + SiO_2 50%, MgO 57.5% + SiO_2 42.5%, and MgO 65% + SiO_2 35%. These analyses show clearly that the main constituents are magnesia and silica, that alumina is present in very small quantities, and that mere traces of sodium, calcium, iron, and chromium are present. The failure to detect potassium spectrographically and the exceedingly small trace of sodium recorded indicate that the alkalis are principally lost by volatilization in the fusion process, a phenomenon to be expected. The iron oxides are almost quantitatively removed by reduction to the metal. If they are not entirely removed, their presence in a particular crystalline phase would be governed by the composition of the melt. Periclase, when it is present, appears to have an affinity for the ferrous oxide and forms magnesio-wüstite. When forsterite is the primary phase, it forms solid solutions. Clinoenstatite likewise forms solid solutions. Owing to the small quantities present in this series, it would be impossible to detect any significant change in the indices of refraction of any of the phases, as may be seen by referring to the graphs given for the refractive indices of the various solid-solution series in the paper by Bowen and Schairer.[3] Alumina, the other impurity as far as is known, does not form solid solutions with the olivines but rather would form a spinel at the close of the crystallization period. If a glass is present in the charge, the alumina most likely would be found there.

The impurities present in the end members of the system involving olivine-magnesite-quartz, as determined by chemical analysis, are iron oxides, small

TABLE XII

PETROGRAPHIC, CHEMICAL, AND SPECTROGRAPHIC ANALYSES OF SOME ELECTRICALLY FUSED OLIVINE CHARGES

Charge No.	Charge	(%)	Chemical analyses		Spectrographic analyses: Main	Small	Trace	Microscopic discussion
14	Olivine	96.4	SiO_2	41.10	Mg	Cr	Na	Thin section, almost all anhedral grains of forsterite in mosaic texture; traces of strongly magnetic, opaque ferrosilicon
	Carbon	1.5	Al_2O_3	0.13	Si	Mn−	Ca	
	Iron	2.1	FeO	0.68		Fe		
	MgO	4.7	MgO	56.50		Al		
				98.41*				
9	Olivine with additions		SiO_2	42.55	Mg	Ca	Ti (0.1%)	Forsterite, ≈99% of thin section; texture distinctly mosaic, grains quite coarse; a few grains of ferrosilicon; olivine (forsterite) shows rare yellowish inclusions of high refractive index at high magnifications; traces of glass in some interstices; optical properties of forsterite: Biaxial (+), α = 1.635, β = 1.650, γ = 1.669, all ± 0.003, $\gamma - \alpha$ = 0.034 (these agree quite well with pure forsterite)
			Al_2O_3	0.43	Si		Cr (0.1%)	
			FeO	0.11			Al	
			CaO	0.27			Mn−	
			MgO	56.92			Fe−	
			Ignition loss	0.19			Ni−	
				100.47†			Cu−	
8	Olivine with additions		SiO_2	43.17	Mg	Ca	Ti (0.1%)	Thin section, about 99% of forsterite with distinct mosaic texture; forsterite crystals may contain very tiny inclusions; small quantity of ferrosilicon with decided metallic luster present; very small quantity of glassy phase
			Al_2O_3	0.37	Si	Al	Cr (0.1%)	
			FeO	0.38			Mn−	
			CaO	0.42			Fe−	
			MgO	56.15			Ni−	
			Ignition loss	0.11			B−	
				100.60†			Cu−	
							P−	

* E. E. Creitz, analyst.
† D. E. Rushing, analyst.

amounts of nickel oxide, chromium oxide, calcium oxide, and alumina. Spectrographic analysis shows the main constituents of the fused charges to be magnesia and silica with small quantities of chromium, manganese, iron, alumina, and traces of calcium, sodium, titanium, nickel, boron, and phosphorus.

These charges were specifically treated with carbon, which eliminated the chromium, nickel, titanium, and most of the iron as metal. The iron that is left is contained in the magnesio-wüstite solid solutions, as shown by the optical data. The quantity of iron oxide present in the charges decreases, in general, as the magnesium content decreases. The reduction to the metallic state has been quite complete in the forsterite-rich charges, inasmuch as the values for the indices of refraction of the forsterite crystals are almost identical with those of pure forsterite. The Bowen and Schairer[3] graph shows that 5% of fayalite raises the value of the β index of a forsterite-fayalite solid solution 0.008. A large proportion of the iron oxide reported in the analyses must be attributed to small globules of reduced metal, which is easily seen on close examination of a fragment with a pocket lens.

X. Conclusions

This electric furnace study of the iron-poor section of the system MgO–FeO–SiO_2, as was expected, is in complete agreement with the precise thermal study of Bowen and Schairer. Crystallization is relatively complete for all charges in which a form of silica is not involved in the equilibrium. Where a polymorph of silica is a stable phase, immiscible liquids, in general, are encountered. Subsequent reheating of a few of these charges causes almost complete recrystallization of clinoenstatite and cristobalite. Other melts merely develop well-crystallized clinoenstatite laths in a glassy base.

These studies also show that impure olivine, rich in the fayalite molecule, may be fused with carbon to produce a highly magnesian olivine that will begin to melt at a much higher temperature than dunite, the natural olivine rock. This quality is valuable in refractories destined for metallurgical purposes.

When the original iron oxide content is significant, as in the olivine-magnesite-quartz series, the optical properties indicate the completeness with which the iron oxides have been removed from the silicates. For those charges lying between olivine and clinoenstatite, the reduction and removal of the oxides of iron is shown to be quite complete by measurement of the optical properties of the phases. Optical studies show that all of the original iron has not been removed from those compositions lying between magnesio-wüstite and forsterite.

XI. Appendix

Inasmuch as certain melts in this study resemble some naturally occurring magnesian rocks, a few comments have been added. Rocks known as dunite and saxonite occur in the vicinity of Webster, North Carolina. Those melts having compositions near that of olivine as well as the improved olivine melts are similar to the naturally occurring dunites. They consist, megascopically, of granular crystalline masses with an open structure. Those charges on the forsterite-clinoenstatite boundary, except for the crystal system of the pyroxene and its very low iron content, are likewise closely related to the saxonites described by Wadsworth[11] and to the meteorites of the stony type,[12] such as the chassignites (olivine) and the amphoterites (olivine with hypersthene).

Acknowledgment

The writers are obligated to T. N. McVay for P.C.E. data and petrographic suggestions; to M. S. Nelson for specific-gravity measurements; to the various analysts cited for the chemical analyses; to E. E. Creitz for spectrographic analyses; and to G. W. Leever, E. F. Nichols, and M. S. Nelson for operation of the arc furnace.

Electrotechnical Laboratory
Bureau of Mines
Norris, Tennessee

---

[11] M. E. Wadsworth, "Lithological Studies," Cambridge, Mass., 1884; the saxonite of Wadsworth is equivalent to the harzburgite of Rosenbusch and the enstatite periodotite of Harker.

[12] W. F. Foshag, "Problems in Study of Meteorites," *Amer. Mineralogist*, **26** [3] 137–45 (1941).

REFRACTORIES SERVICE CONDITIONS IN THE BLAST FURNACE *

By Hobart M. Kraner

Abstract

An analysis of "how a blast-furnace lining wears out" is presented. The conclusions drawn are the result of critical studies on three furnaces as their linings were being removed for relining. Scab and scab-refractory interface samples were taken at 3-ft. intervals. These were analyzed and studied petrographically. Alkali attack and carbon disintegration are concluded to be the most serious causes of lining wear and deterioration in the stack, whereas insufficient refractoriness and high porosity are concluded to be the sources of trouble in the hearth.

I. Introduction

Two million-ton blast-furnace linings are not sufficiently common to warrant the assumption that a great proportion of our present installations will produce such tonnages. Linings which have a far shorter life than this, moreover, appear to be the general rule. The steel industry, however, spent about one million dollars annually between 1935 and 1940 on blast-furnace refractories, and the figures for 1940 and 1941 will greatly exceed this amount. The industry would like to reduce this expense as well as the far greater cost of installation.

There are two schools of thought on the question of increased blast-furnace campaigns. There is a minority of opinion that, after what is now considered to be a fair lining life, the mechanical equipment will need repairs and that longer lining life is not of primary importance. This view does not seem to be tenable inasmuch as the condition of the lining is generally the deciding factor in the termination of a campaign. The mechanical equipment may also be redesigned to keep step with the extended use of linings if the latter can be achieved. The amount of operating time lost in relining a furnace and the cost of the equipment obviously have an important bearing on the cost of the general plant operation.

The present campaigns are unquestionably longer than those of twenty years ago, but producers who believe that greater possibilities are ahead know that additional data on the mechanism of lining wear must be obtained before any development beyond the present status can be reached. A complete record of data on refractory linings is imperative in order to conduct intelligent tests on the suitability of refractories for this purpose and for ultimate specifications of the proper brick for future use. This paper might therefore be entitled, "Mechanism of Wear of Blast-Furnace Linings," because it is toward a better understanding of this problem that the attention of the users of such refractories has been directed.

This study is not a virgin field as the appended Bibliography† indicates. Some excellent papers are included in this list, each dealing with a specific phase of the problem. Judging from this literature and the results of recent critical studies of worn linings, present-day linings deteriorate by the same processes reported more than forty years ago. Included among these types of destructive action are carbon deposition and disintegration and alkali and slag attack. This statement is not meant to imply that no improvements have been made in the refractories being produced. It stresses the point, however, that all of the ills of the past are still present and are making themselves felt.

The literature does not reveal which one of these difficulties is the most serious or to what extent improvements in refractories have changed the ranking of these influences in the order of their detrimental effects. Neither is it stated clearly what has been done to cure the defects.

Blast-furnace workers frequently express their ideas on the subject, but some of these opinions have little value to the ceramic engineer because the criticism is not made from a ceramic viewpoint. Refractories manufacturers, on the other hand, lack the experience of the blast-furnace operator and the frequent opportunity to inspect worn linings, both of which aid in the diagnosis of the defects as well as in presenting a critical analysis. For a constructive analysis, therefore, both groups should work together.

The analysis which follows is based chiefly on a search of the literature, supplemented by careful chemical and mineralogical studies of a number of worn linings, as indicated in Tables I, II, and III and in Figs. 1 to 7, inclusive. A rather complete picture is presented of the reactions that occur in the furnace lining during a campaign, and it is hoped that this study will indicate

Fig. 1.—Brickwork in upper part of furnace in which wear has not been severe.

* Presented at the Refractories Division Autumn Meeting, Uniontown, Pa., September 6–7, 1940. Received December 11, 1941.

† See Bibliography, pp. 318–20.

TABLE I

COMPARISON OF REFRACTORIES MATERIAL PRACTICE IN THE UNITED STATES AND IN GREAT BRITAIN*

Finished brick analysis	Locality from Which Fire Clay Is Obtained and Details of Strata							
	(1)†			(2)†		(3)†	(4)‡	(5)‡
	Kentucky sandstone measures and Pa. coal measures Woodland					Kentucky sandstone measures	North Tyne area coal measures	Stourbridge district coa measures
	Hearth and bosh	Inwall	Top	Olive Hill, Ky.	GRCo, Pa.			
Silica	53.1	53.8	55.1	51.5	52.12	57.28	54.40	65.31
Alumina	42.5	41.5	39.6	42.09	41.69	38.50	38.14	29.82
Ferric oxide	2.4	2.5	2.6	2.14	2.42	2.80	2.87	1.64
Lime	0.34	0.39	0.52	0.47	0.38	0.42	0.66	0.33
Magnesia	0.38	0.42	0.46	0.49	0.29	0.32	0.97	0.26
Alkalis	1.55	1.75	2.08	0.80	1.71	1.10	1.52	1.54
Titanium oxide	§	§	§	1.80	2.18	§	0.58	1.22
Brick fusing temp. (°F.)	3100–3130	3070–3100	3040	Approx. 3270		3100	3110–3180	3000

* Fred Clements, Blast-Furnace Practice. Ernest Benn, Ltd., London, 1929.
† Column (1): Harbison-Walker Refractories Co., Pittsburgh, Pa.; (2) General Refractories Co., Philadelphia, Pa.; (3) Ashland Fire Brick Co., Ashland, Ky.
‡ Column (4): Henry Foster & Co., Ltd., New Castle-on-Tyne; (5) King Bros. (Stourbridge), Ltd., Stourbridge.
§ No data given.

TABLE II

TYPICAL REFRACTORIES FOR BLAST-FURNACE LININGS*

	Hearth and bosh	Inwall				Hearth and bosh	Inwall		Hearth and bosh	Inwall	Top
	A	B	C	D	E	F	G	H	I	J	K
SiO_2	51.2	51.80	51.4	52.2	53.3	53.80	53.5	54.40	52.3	51.78	53.8
FeO	0.3	0.36	0.2	0.2	0.1	0.24	0.2	0.28	0.2	0.36	0.2
Fe_2O_3	2.6	2.26	3.1	2.1	2.1	2.17	1.7	1.60	1.6	2.14	2.4
Al_2O_3	39.5	39.96	39.6	40.6	39.4	38.40	39.6	38.45	41.0	40.83	38.2
CaO	0.2	0.52	0.3	0.1	0.1	0.32	0.1	0.44	0.2	0.24	0.2
MgO	0.5	0.36	0.5	0.3	0.3	0.68	0.3	0.72	0.4	0.46	0.4
TiO_2	2.7	2.77	2.6	2.4	2.3	2.23	2.4	2.15	2.4	2.70	2.17
Alkalis (total)	2.5	1.22	1.7	1.7	1.8	1.83	1.6	1.61	1.4	1.25	1.6
Sp. gr. (true)	2.639	2.732	2.724	2.685	2.726	2.723	2.734	2.712	2.720	2.73	2.706
Sp. gr. (bulk)	2.131	2.218	2.157	2.170	2.311	2.348	2.278	2.287	2.290	2.236	2.280
P. C. E.	32½–33	32½	31–32½	32½–33	33	33	32½	32	32½	32½	32½–33
Temp. (°F.)	3137–3173	3137	3056–3137	3137–3173	3173	3173	3137	3092	3137	3137	3137–3173
True porosity (%)	19.2	18.9	20.8	19.1	15	13.7	16.7	15.7	15.4	18.0	15.7

* Data for 1940.

the lines along which refractories producers should direct their efforts in order to furnish better blast-furnace refractories.

II. Disintegration by Carbon Deposition

The greatest amount of study, up to the present time, apparently has been centered on the disintegration of refractory products caused by a deposition of carbon and the swelling of this carbon in the pores of the refractory.

Some men do not agree that carbon disintegration is a serious matter as based on the present life of a furnace lining. A critical study, however, cannot fail to reveal that this problem is complex and that it must be corrected if the life of a furnace lining is to be extended. Such failures may occur at an early stage in a campaign as a result of unfavorable temperature and atmospheric conditions. Two furnace failures coming under the personal observation of the writer could be thus explained, and the defects were corrected in subsequent lining installations.

The process by which such disintegration takes place was an early discovery and was recognized by Gruner* in 1870 to 1873. Metallic iron, Fe_2O_3, Fe_3O_4, carbides, and zinc are generally understood to be the principal catalysts that accelerate the reaction which precipitates carbon within the pores of the refractory, as follows:

$$2CO \rightleftarrows C + CO_2.$$

In spite of the available literature on this subject, little quantitative information is available on the relative importance of these catalysts. This lack of data also explains why the iron oxide content of a refractory cannot be used to determine quantitatively the ability of the refractory to withstand disintegration by carbon deposition.

There is still a great deal to be learned regarding the fundamentals of this entire reaction and of the effect of atmospheric pressure, alkalis, and other compounds not

* See Bibliography, reference 1, p. 318.

TABLE III

ANALYSES* OF HEARTH BRICK SHOWN IN FIG. 11

Sample No.	Porosity	Metal Fe	FeO	Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO	K_2O	MnO	TiO_2	C	S	CO_2	Total
1	0.5	0.53	2.53	0.57	53.30	37.43	0.40	0.54	2.38	0.09	1.63	0.10	0.05	0.13	99.68
2	6.6	8.26	0.64	0.14	47.90	36.09	0.40	0.51	1.82	0.26	1.60	1.78	0.06	0.05	99.51
3	3.5														
4	0.2	6.66	5.76	0.29	48.20	32.99	0.30	0.20	1.70	0.61	1.88	0.45	0.10	0.18	99.32
5	10.6	0.44	1.65	0.63	54.12	35.79	0.80	0.50	2.77	0.06	1.73	0.11	0.09	0.14	98.83
6	4.4	0.60	1.24	1.43	54.06	38.26	0.30	0.15	1.26	0.06	2.08	0.12	0.06	0.08	99.70
7	4.6	1.60	1.03	0.23	54.40	37.04	0.64	0.23	1.22	0.81	2.10	0.26	0.08	0.07	99.71
8	4.7	0.96	1.98	1.03	53.40	36.25	0.20	0.43	2.69	0.08	2.22	0.09	0.14	0.20	99.67
9	18.0	0.44	2.55	0.20	50.50	34.68	0.40	0.93	3.38	0.05	2.08	0.59	0.08	0.27	96.15
10	2.3	0.44	1.85	2.23	54.90	34.96	0.60	0.29	1.80	0.05	2.23	0.26	0.07	0.06	99.74
11	18.8	0.32	1.34	0.57	53.70	38.41	0.20	0.36	2.23	0.05	2.08	0.10	0.05	0.17	99.58
12	6.5	0.92	1.24	0.86	53.70	36.68	0.68	0.93	2.12	0.08	2.08	0.20	0.10	0.07	99.66
13	12.6	2.56	2.73	0.29	50.90	36.48	0.80	0.51	2.02	0.17	2.35	0.42	0.14	0.21	99.58
14	13.8	1.76	0.82	1.26	49.60	36.93	2.40	1.18	2.63	0.13	2.08	0.42	0.10	0.20	99.51
15	12.2	2.72	1.13	0.57	46.50	37.00	0.20	0.57	6.07	0.04	2.08	0.36	0.14	0.54	98.93

* Analyses for Na_2O included in K_2O except sample No. 15, which is 1.01%.

FIG. 2.—Brickwork below that shown in Fig. 1 where disintegrated zone begins to appear; the unaffected section at the left is being peeled off with little effort with a crowbar; several tons of this brickwork face dropped just after this picture was taken; a heavy wall of unaffected brickwork is shown between the disintegrated zone and the shell.

FIG. 3.—Section of worn lining lower down in wall where "bellying" begins to take place; the disintegrated zone is closer to the shell, and the relatively unaffected zone is thin; the alkali attack has reduced the face to only 4 in. thickness, and the disintegrated zone is considerably closer to the shell than farther up in the wall as shown in Fig. 2.

previously mentioned. This subject is open to and worthy of considerable chemical research by the refractories manufacturer if he is to improve his products in this respect. The procedure of the test is relatively simple.

III. Alkali Attack

Alkali attack is next in importance, possibly nearly as important as carbon deposition. The writer has found that this action occurs in the upper part of the bosh and in the lower part of the stack. Small amounts of alkalis in the constituents of the furnace burden volatilize and penetrate into the refractories; the large amounts are accumulations from the same source.

FIG. 4.—Brick taken from between the shell and the disintegrated zone; the end on the right has extended into the disintegrated zone and shows evidence of breakdown by CO disintegration.

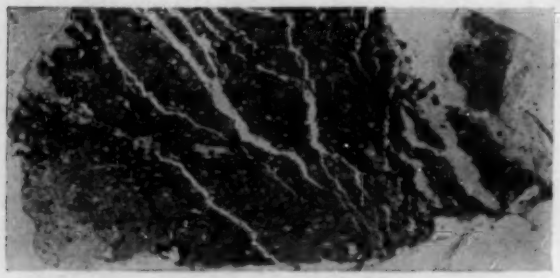

FIG. 5.—Brick weakened and broken down by carbon disintegration into which lead has penetrated, indicates that breakdown occurred at a relatively low temperature where the lead was flowing into all available cracks; cracks may have been increased by shifting of wall load; white areas are seams of lead.

FIG. 6.—Bronze bosh cooler protruding through scab; water cooling of bosh is sufficient to maintain refractories.

These alkalis react with the brickwork to form nephelite ($Na_2O \cdot Al_2O_3 \cdot 2SiO_2$), and microsections show the plastic fire clay to have been almost entirely dissolved. Because the brick have the approximate composition of $Al_2O_3 \cdot 2SiO_2$, the formation of nephelite is normal if all other conditions are favorable. The presence of large amounts of nephelite in the brick-scab interface shows that the brick have been fluxed and that the high alkali

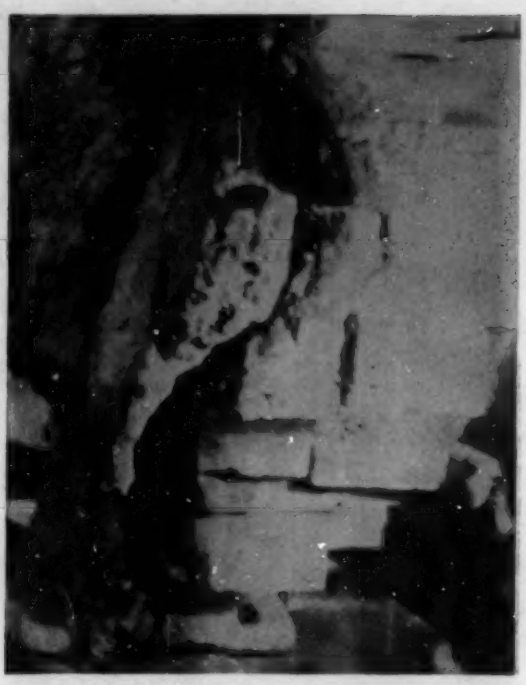

FIG. 7.—Cross section of bosh wall; bosh coolers have been removed, but the temperature contours (as they existed in the brickwork) are apparent in the shape of the attacked zone, being thicker midway between the coolers than in the immediate vicinity of the coolers.

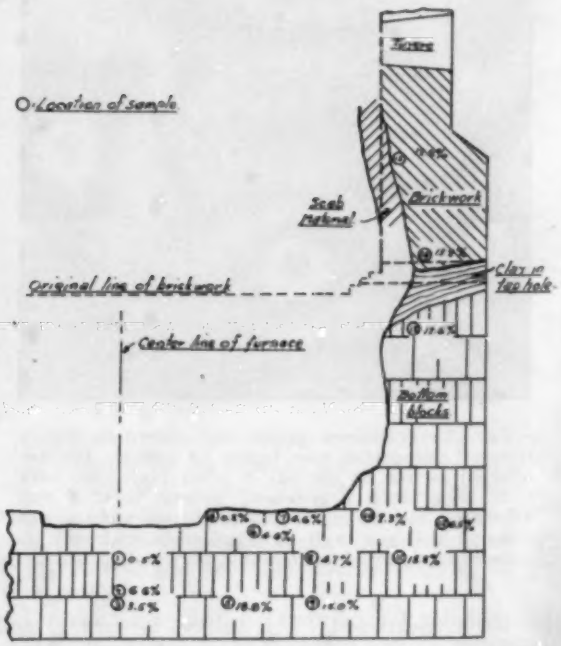

FIG. 8.—Hearth lines and percentage of porosity of hearth refractories (see Table III); note vitrified character of brick in face of hearth and absence of contaminants which might have contributed to vitrification.

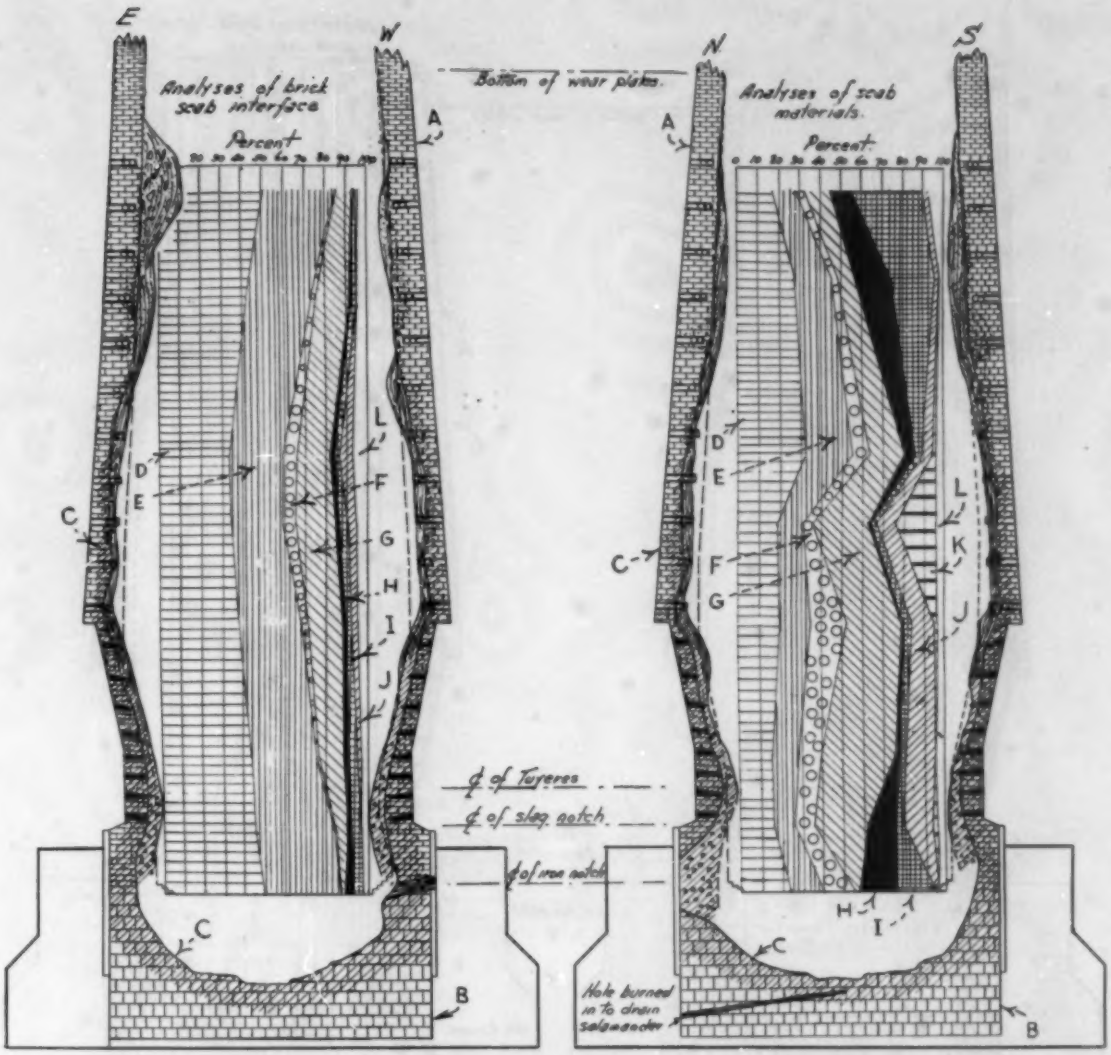

FIG. 9.—Chemical analyses of scab and brick interface of a blast-furnace lining; *A*, brickwork; *B*, bottom blocks; *C*, fused areas; *D*, SiO_2; *E*, Al_2O_3; *F*, carbon; *G*, alkalis; *H*, CaO and MgO; *I*, Fe, FeO, and Fe_2O_3; *J*, CO_2; *K*, ZnO; *L*, MnO, S, and TiO_2.

content of samples which were collected from this zone of the furnace is not simply impregnation as would be suspected if chemical analyses only had been obtained. The nephelite is really a reaction product which also gives an indication of the course of the reaction. This alkali naturally lowers the fusion temperature of the brick.

IV. Slag Attack

The term "slag attack" as applied to blast-furnace refractories has been used rather carelessly. Blast-furnace slag is not guilty of much refractory attack except in the bosh and upper hearth sections. Inasmuch as the coke is not burned and the ash is not available until it reaches the bosh, this slag exists only in the lower bosh section. The hearth is water jacketed, and the bosh is extensively water cooled by copper bosh cooling plates which extend through the lining. The bosh refractories other wise would last only a short time owing to the high temperature and corrosive action of the basic slag-forming constituents.

Little slag action occurs above the mantle because little coke ash is present to form slag above that point. Although lime and iron oxide might be expected to flux the refractories above the mantle, there is not much evidence that this occurs. Only minor quantities of lime-bearing minerals are present in the brick-scab interface, and the amount of lime and magnesia that is found by chemical analysis is also small.

V. Abrasion Defects

The serious effect of abrasion on blast-furnace linings has been studied.* Some operators place particular stress on the severity of this condition in their individual

* See Bibliography, section (4), p. 320.

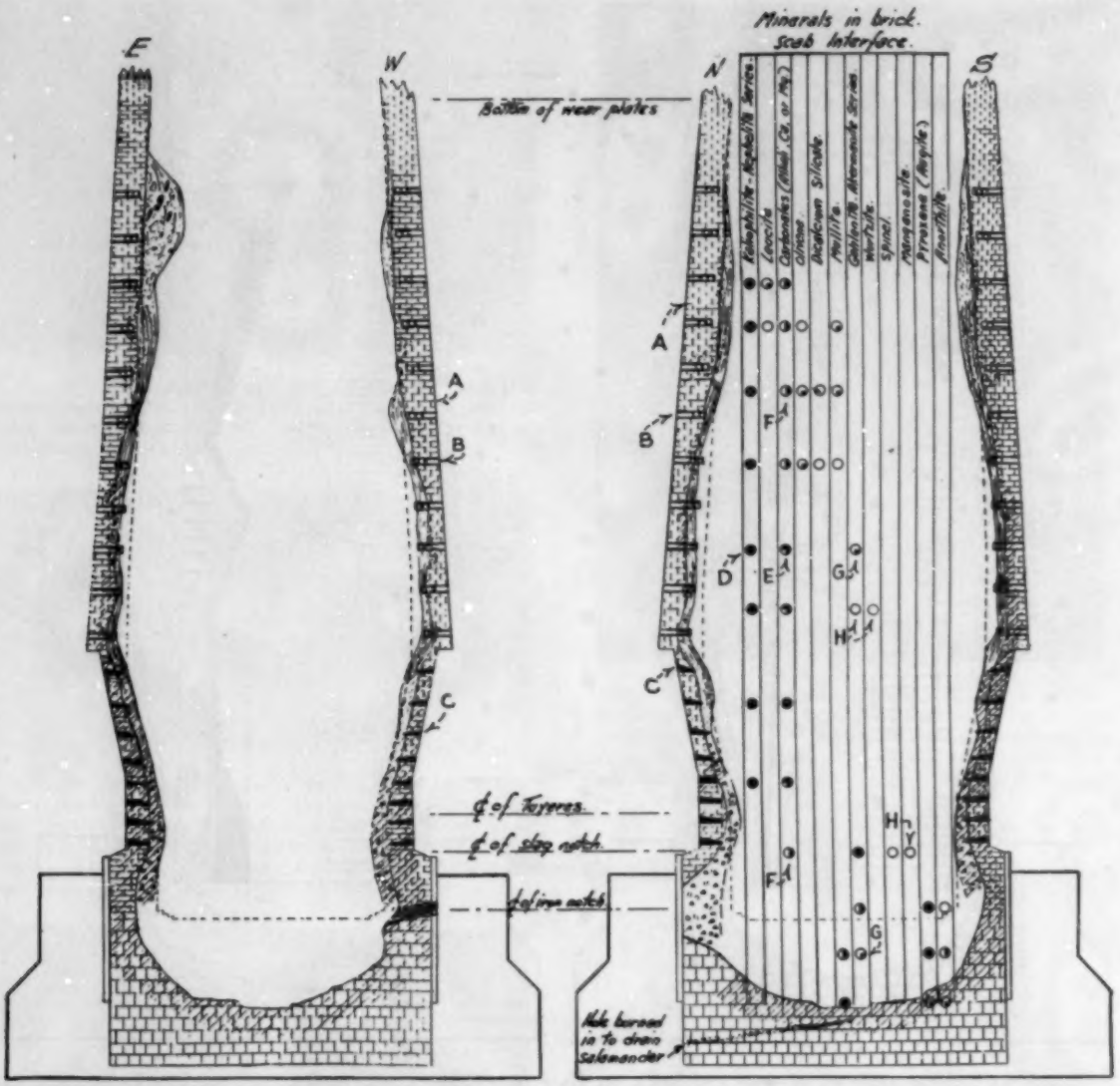

FIG. 10.—Minerals found in brick-scab interface of blast-furnace lining; *A*, brickwork; *B*, cast-iron stack cooler; *C*, copper bosh cooler; *D*, dominant mineral; *E*, present in large amount; *F*, present in moderate amount; *G*, present in small amount; *H*, present as occasional grains.

cases because of the prescnce of certain ores or sinters in the burden. Judging from what has been seen in blown-out furnaces, abrasion, as such, is believed to be only a secondary cause of lining wear. The top section of the lining undergoes direct abrasion from the impingement of the charge as it falls from the bell, but it is alleviated by metal-wearing plates which are anchored in the lining in this section. The blown-out lines further down in a furnace usually show considerable scab on which the abrasion takes place. Wear in this section probably occurs when relatively large pieces of scab break off and carry with them loose, weak pieces of disintegrated or fused refractory. The breakdown and weakening of the refractory that is responsible for this condition is caused by carbon disintegration, alkali reaction, or both.

In the zone about one third of the way down from the top to the mantle, the disintegrated area is fairly close to the working face. Disintegration in this region appears to contribute heavily toward the breaking away of thin layers of good refractory. Scabs form and break off through zones of the brick which have been weakened by carbon disintegration.

The scabs which form on the lining further down take the brunt of the descending charge. Only a small part of this scab is firebrick, and it usually consists of the consolidation of stock, alkalis, and small lumps of brick which find their way into the descending burden. The zone between the scab and the solid brick contains lumps of brick which have disintegrated but which have not been consolidated. The effects of the so-called abrasion, based on these observations, apparently

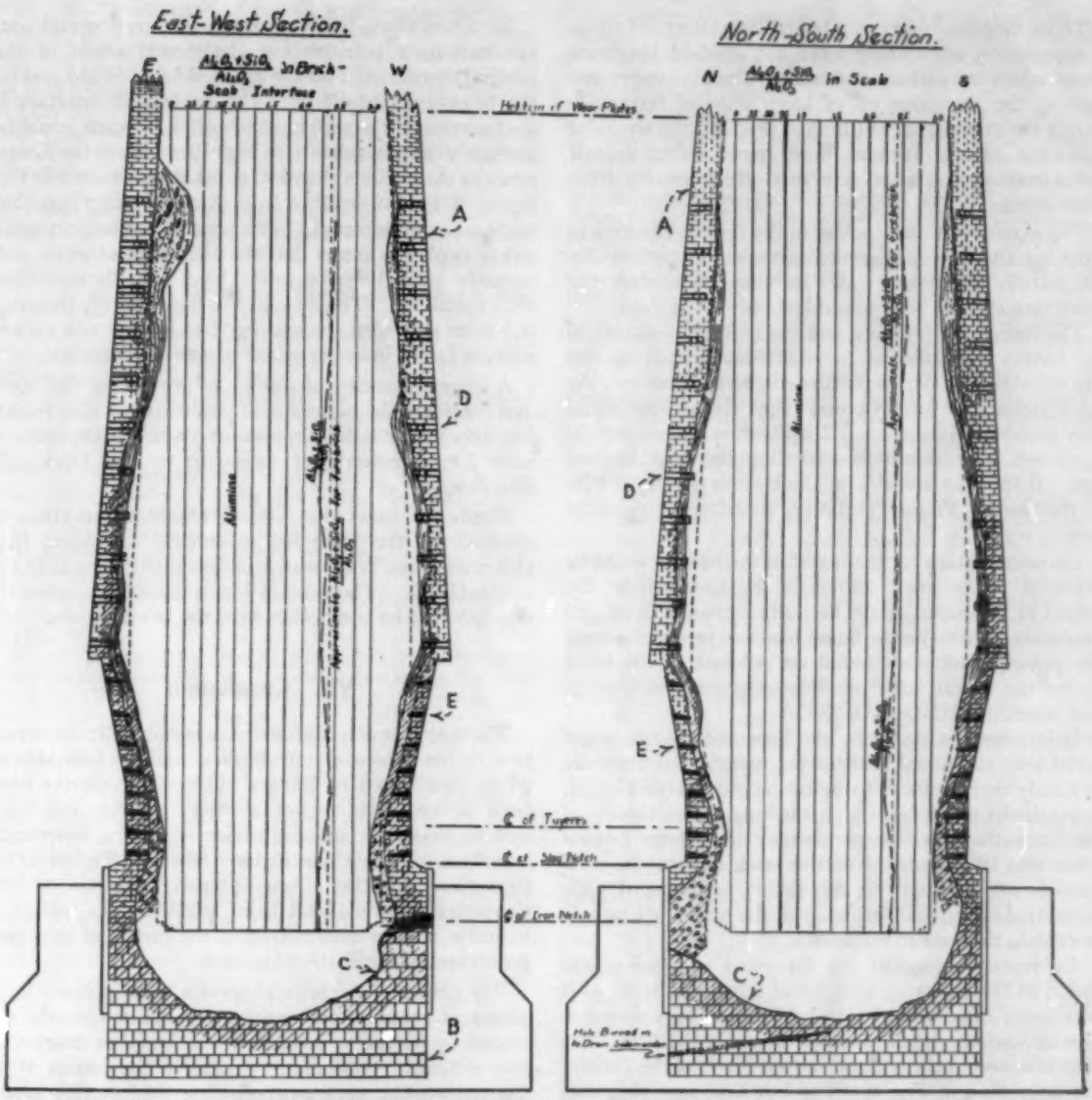

FIG. 11.—Silica ratio of samples from brick-scab interface showing that refractory has been penetrated but not leached; *left*, east-west section; *right*, north-south section; *A*, brickwork; *B*, bottom blocks; *C*, fused areas; *D*, cast-iron stack cooler; *E*, copper bosh coolers.

should be assigned to the pressure of the descending charge which breaks the scab from the brick face. As a result of the altered condition of a brick face, which has been weakened by carbon deposition and alkali attack, large sections of scab may be removed in this manner.

VI. Disintegration Caused by Combined Action

The combined action of carbon disintegration and alkali attack is responsible for the bellied lines a short distance above the mantle, and it operates somewhat in the following manner:

The intense zone of carbon disintegration develops at 450° to 550°C. This zone is wider at the top than at the mantle, and it is near the inner face at the top and closer to the shell at the mantle. High temperatures and severe alkali attack are also encountered at the mantle. As the alkali reaction removes the brick face, the temperature gradient between the working face and shell changes and the disintegrating zone advances toward the shell. Alkali attack and the advancing disintegrating action therefore proceed simultaneously.

By the time alkali attack has removed part of the brickwork, the temperature of which is always above 550°C., carbon disintegration has been so effective near the shell that practically nothing remains to support the upper brickwork!

Irregularities in the slag analyses, especially in the alumina content, are frequently observed, and these are generally considered to be due to the sloughing off of such unsupported slabs inside the weak, disintegrated zone.

Those manufacturers who belittle the effect of carbon disintegration apparently have not studied the combined effect of carbon and alkali directly above the mantle, the sloughing off of large slabs of refractory during the removal of old linings (Fig. 2), the irregular operation of the furnace, and many other telltale indications of the loose structure which results from these causes.

The extensive water cooling in the bosh is effective in reducing the rate of chemical attack and carbon disintegration. Without water cooling, moreover, the refractories in the bosh would last only a few days.

The ferrostatic pressure and the high temperature in the hearth are sufficient to vitrify the brick face (see Fig. 8). Before vitrification is complete, however, the brick frequently are so porous that the molten metal may penetrate into them. Vitrification causes shrinkage which may be sufficient to allow the brick to float out. Brick that are $4^1/_2$ in. thick often shrink to 4 in. in this zone. Volume stability, therefore, is essential here.

Chemical attack by the metal in the hearth would be expected to be low. Although the iron sulfide dissolved in the metal might be quite corrosive, lime and magnesia seem to be the fluxes that are present because the principal minerals found on the face of the brick under the metal bath are lime-magnesia compounds and anorthite ($CaO \cdot Al_2O_3 \cdot 2SiO_2$).

It is not clear just how the lime and magnesia get down into the metal bath in the hearth, but they are probably carried under by agitation of the liquid metal. Some doubt might be cast on the lime-attack theory on the basis that these minerals may have been formed when slag was spread over the brick face as the salamander was drained. If this theory is discarded, only the actual fusion and shrinkage of the brickwork remain to explain the wear in the hearth.

Evidence to support the foregoing conclusion was found in the following analysis of a furnace lining as it was being removed prior to relining. The concentration of various chemical constituents in the brick-scab interface and in the scab at various levels of the furnace are presented in Fig. 9. The low lime and magnesia content of the brick-scab interface and the high alkali content are clearly shown in this figure.

The scab above the mantle has a high alkali content. The carbon, lime, and magnesia contents, as might be expected, are also higher in this scab than in the brick-scab interface.

To differentiate between simple penetration and contamination, a petrographic study was made of the mineral distribution on the exposed faces (scab) and on the brick-scab interfaces. The brick-scab interface is that portion of the wall in which brick, as such, could be definitely distinguished (see Fig. 10). From the occurrence of the various chemical constituents shown in this figure, it is also possible to deduct the reactions that have actually occurred. The presence of large quantities of nephelite shows that the alumina and silica, presumably from the refractories, have actually combined with the alkali. The quantity of lime-bearing minerals is low in this zone, indicating that lime is not an important factor in lining attack above the mantle.

A larger quantity of olivine is present in the scab, and considerable quantities of nephelite are also found, but this factor is less important than the presence of such large amounts of nephelite in the brick-scab interface.

Figure 11 shows the ratio of alumina plus silica to alumina for the foregoing specimens, indicating that this ratio in the brick-scab interface is the same as in the original brick. The penetration of the alkali apparently was followed by a reaction with the brick *in situ*.

VII. Conclusions

The operator of a blast furnace is rightfully conservative in his choice of refractories, and he hesitates to adopt new types of linings unless their merits have been proved. He is not always "ceramic minded," and he must rely on the advice of others, frequently outsiders, to guide him in his decision. Technical information resulting from intensive studies of the chemistry involved and from reliable tests will be a valuable help in demonstrating the merits of new proposals and in eliminating his fears.

The results of refractories service tests in many large pieces of metallurgical equipment are frequently obscured by operating variables, which makes interpretation difficult. Systematic studies of the causes of refractories wear, such as those described in this paper, make it possible to separate the various contributing factors so that the effects of each may be studied separately under controlled conditions in the laboratory. This procedure, furthermore, yields positive and immediate results in aligning refractories according to their merits.

Bibliography*

(1) Early Studies

1. M. L. Gruner, Studies of Blast-Furnace Phenomena, pp. 126–27. Henry S. King & Co., London, 1873.
2. John Pattinson, "Carbon and Other Deposits from Gases of Blast Furnaces in Cleveland," *Jour. Iron & Steel Inst.* [*London*], **1**, 85–100 (1876).
3. Limbor, "Destructive Action of Blast-Furnace Gases," *Wochschr. Ver. Deut. Ingen.*, p. 259 (1878).
4. John Pattinson, *Bull. de Industrie Minerale*, [2d series], p. 483 (1881).
5. L. Mond and F. Quincke, "Volatile Compound of Iron and Carbonic Oxide," *Proc. Chem. Soc.*, **7** [100] 117–18 (1891); *Jour. Soc. Chem. Ind.*, **10**, 644 (1891).
6. F. W. Lurman, "Preservation of Refractories in Blast Furnace," *Stahl u. Eisen*, **20** [Nov. 1] 1104–1105 (1900).
7. G. M. Hohl, "Brick Column Lifts Furnace Top," *Iron Trade Rev.*, **72**, 1813–19 (1903).
8. B. Osann, "Action of Destructive Influence on Refractory Brickwork in Iron Mills," *Stahl u. Eisen*, **23** [14] 823–29 (1903).
9. F. Firmstone, "Alteration of Firebrick by Furnace Gases," *Trans. Amer. Inst. Mining Met. Engrs.*, **34**, 427–31 (1904).

* Five categories of refractories disintegration are given; the order is chronological except in a few instances where the papers have been published in series.

10. F. ZIMMERMAN, "Experimental Studies on Processes in the Blast Furnace: I, Division of Carbon Monoxide," *Stahl u. Eisen*, **25** [July 1] 758–62 (1905).

11. R. SCHENK AND W. HELLER, "Experimental Studies on Processes in the Blast Furnace," *ibid.*, **25** [October 1] 1121–24 (1905).

12. S. HILPERT AND T. DIECKMANN, "Iron Carbides and Their Catalytic Action on Decomposition of Carbon Monoxide," *Ber.*, **48**, 1281–36 (1915).

(2) Carbon Monoxide Disintegration of Refractories

13. R. M. HOWE, "Blast-Furnace Refractories (Appendix)," *Trans. Amer. Inst. Mining Met. Engrs.*, **62**, 161–67 (1920).

14. L. P. ROSS, "Failure of Blast-Furnace Stock Line Brick," *Iron Age*, **105**, 117–18 (1920).

15. P. O. MENKE, "Disintegration of Blast-Furnace Linings," *Blast Furnace & Steel Plant*, **10**, 116–18 (1922); *Ceram. Abs.*, **1** [7] 181 (1922).

16. R. M. HOWE, discussion on "Disintegration of Blast-Furnace Linings," *Blast Furnace & Steel Plant*, **10**, 161–63 (1922); *Ceram. Abs.*, **1** [7] 181 (1922); see reference 15.

17. C. E. NESBITT AND M. L. BELL, "Firebrick Disintegration," *Brick & Clay Rec.*, **62**, 1042–43 (1923); *Ceram. Abs.*, **2** [10] 223 (1923).

18. B. M. O'HARRA AND W. J. DARBY, "Disintegration of Refractory Brick by Carbon Monoxide," *Jour. Amer. Ceram. Soc.*, **6** [8] 904–14 (1923).

19. S. M. PHELPS, discussion on "Disintegration of Clay Refractories in Iron-Blast Furnaces," *ibid.*, **7** [9] 716–17 (1924).

20. E. DIEPSCHLAG AND K. FEIST, "Disintegration of Blast-Furnace Refractories by Carbon Monoxide," *Feuerfest*, **4** [9] 133–36 (1928); *Blast Furnace & Steel Plant*, **17**, 280–82 (1929); *Ceram. Abs.*, **8** [3] 193 (1929).

21. F. C. HOWARD, "Carbon Deposition near Furnace Top," *Iron Age*, **122**, 271 (1928).

22. H. K. MITRA AND ALEXANDER SILVERMAN, "Prevention of Disintegration of Blast-Furnace Linings," *Jour. Amer. Ceram. Soc.*, **11** [5] 278–91 (1928).

23. H. A. BERG, "Blast-Furnace Developments in 1928," *Blast Furnace & Steel Plant*, **17** [1] 67–68 (1929); *Ceram. Abs.*, **8** [4] 274 (1929).

24. F. CLEMENTS, Blast-Furnace Practice, pp. 134–35. Ernest Benn, Ltd., London, 1929; *Ceram. Abs.*, **8** [12] 897 (1929).

25. R. P. HEUER, discussion on "Prevention of Disintegration of Blast-Furnace Linings," *Jour. Amer. Ceram. Soc.*, **12** [1] 30–31 (1929); see reference 22.

26. D. E. HUBBARD AND W. J. REES, "Dissociation of Carbon Monoxide in Contact with Refractory Materials," *Trans. Ceram. Soc.* [England], **28** [6] 277–307 (1929); *Ceram. Abs.*, **8** [11] 816 (1929).

27. W. HUGILL, H. ELLERTON, AND A. T. GREEN, "Action of Carbon Monoxide on Refractory Materials: I, Experiments on Disintegration of Fire-Clay Products by Carbon Monoxide; II, Further Experiments on Disintegration of Fire-Clay Products by Carbon Monoxide," *Inst. Gas Engrs., 22nd Rept., Refrac. Materials Joint Sub-Committee, Copyright Communication*, No. 39, pp. 26–30; pp. 30–33 (1931); Parts I and II, *Bull. Brit. Refrac. Research Assn.*, No. 25, pp. 14–23; No. 26, pp. 37–43 (1931); *Trans. Ceram. Soc.* [England], **32** [12] 533–42; 543–50 (1933); *Ceram. Abs.*, **11** [9] 493 (1932); **13** [10] 264 (1934); "III, Experiments (*a*) with Laboratory-Prepared Specimens and (*b*) Influence of Reheating Disintegrable Products," *Inst. Gas Engrs., Copyright Pub.*, No. 61, pp. 42–46 (1932); "IV, Deposition of Carbon on Certain Ferruginous Substances," Part III, *Bull. Brit. Refrac. Research Assn.*, No. 28, pp. 64–69 (Aug., 1932); Part IV, *ibid.*, No. 31 (June, 1933); Parts III and IV reprinted in *Trans. Ceram. Soc.* [England] **37** [1] 6–11; 12–16 (1938); *Ceram. Abs.*, **12** [6] 228 (1933); **17** [7] 253 (1938).

28. "Carbon Monoxide and Refractory Materials," *Feuerungstech.*, **20** [2] 29 (1932); *Ceram. Abs.*, **11** [5] 309 (1932).

29. F. H. CLEWS AND A. T. GREEN, "Significance of Permeability to Gases in Relation to Texture and Industrial Usage of Refractory Materials," *Bull. Brit. Refrac. Research Assn.*, No. 27 (March, 1932); reprinted in *Trans. Ceram. Soc.* [England], **33** [2] 56–72 (1934); *Ceram. Abs.*, **13** [8] 212 (1934).

30. F. HARTMANN, "Destruction of Blast-Furnace Linings," *Stahl u. Eisen*, **52** [44] 1061–66 (1932); *Ceram. Abs.*, **12** [3] 111 (1933).

31. J. W. MELLOR, Comprehensive Treatise on Inorganic and Theoretical Chemistry, Vol. XII. Longmans, Green & Co., Ltd., London, 1932. 944 pp.; *Ceram. Abs.*, **12** [5] 207; [10–11] 403 (1933).

32. W. J. REES, "Blast-Furnace Linings," *Brit. Clayworker*, **41** [481] 54–56 (1932); *Ceram. Abs.*, **11** [9] 494 (1932).

33. VEREINIGTE STAHLWERKE A.-G., "Refractory Materials," French Pat. 740,467, July 25, 1932; *Ceram. Abs.*, **12** [8] 302 (1933).

34. H. W. HIBBOTT AND W. J. REES, "Influence of Cyanogen on Reduction of Carbon Monoxide in Contact with Refractory Materials," *Trans. Ceram. Soc.* [England], **32**, 253–69 (1933); *Colliery Guard*, **145** [3744] 646 (1932); *Ceram. Abs.*, **12** [1] 20 (1933); *Refrac. Jour.*, **8** [10] 368–78 (1932); *Ceram. Abs.*, **12** [2] 63 (1933).

35. P. P. BUDNIKOV, "Destruction of Grog Brick by Carbon Monoxide," *Novosti Tekhniki*, No. 26, p. 11 (1934); abstracted in *Referat. Silikatliteratur*, No. 612 (1934); *Ceram. Abs.*, **15** [1] 21 (1936).

36. R. N. GOLOVATNIĬ AND I. A. SMOLYANITZKIĬ, "Changes in Chemical Composition of Refractories for Blast-Furnace Use During Their Service," *Ogneupory*, **2** [12] 21–25 (1934); *Ceram. Abs.*, **14** [11] 278 (1935).

37. P. J. HOLMQUIST, "Precipitation of Carbon on Blast-Furnace Brick," *Jernkontorets Ann.*, **118**, 519–30 (1934); abstracted in *Chem. Zentr.*, **1935, I**, 2063; *Ceram. Abs.*, **14** [10] 250 (1935).

38. N. M. LOZINSKIĬ AND E. I. TER-MIKAELYANTZ, "Influence of Carbon Monoxide on Grog Materials," *Ogneupory*, **2** [12] 18–20 (1934); *Ceram. Abs.*, **14** [11] 280 (1935).

39. S. M. PHELPS, "Action of Gas Atmospheres on Refractory Materials," *Amer. Refrac. Inst., Tech. Bull.*, No. 48, 11 pp. (1934); *Ceram. Abs.*, **13** [10] 264 (1934).

40. W. H. WETHERILL AND C. C. FURNAS, "Rate of Reduction of Iron Ores with Carbon Monoxide: Effect of Particle Size, Gas Velocity, and Gas Composition," *Ind. Eng. Chem.*, **26** [9] 983–91 (1934); *Ceram. Abs.*, **16** [3] 97 (1937).

41. C. E. NESBITT, "Disintegration of Firebrick Linings in Iron-Blast Furnaces," *Crucible*, **19**, 54 (1935); *Chem. Abs.*, **29**, 3476 (1935); *Ceram. Abs.*, **14** [9] 219 (1935).

42. C. C. FURNAS, "Kinetics of Some Reactions of Interest to Ceramists; Disintegration of Blast-Furnace Linings Due to Carbon Deposition," *Jour. Amer. Ceram. Soc.*, **19** [6] 177–86 (1936).

43. R. N. GOLOVATNIĬ, "Effect of Chemical Composition of Refractories on Separation of C According to the Reaction $2CO \rightleftarrows CO_2 + C$," *Ogneupory*, **4**, 686–91 (1936); abstracted in *Chem. Zentr.*, **1937, II**. 2053; *Ceram. Abs.*, **17** [2] 71 (1938).

44. R. A. LINDGREN, "Refractories for Iron-Blast Furnaces," *Amer. Inst. Mining Met. Engrs. Tech. Pub.*, No. 752, 16 pp. (1936); *Mining Tech.*, **1**, No. 1 (1937); *Ceram. Abs.*, **17** [1] 21 (1938).

45. K. PUKALL, "Rapid Test of Resistance of Refractories to Carbon Monoxide," *Sprechsaal*, **71** [26] 321–24 (1938); *Ceram. Abs.*, **19** [1] 15 (1940).

46. J. STOECKER AND A. REIN, "Developments in Blast-Furnace Lining," *Stahl u. Eisen*, **58**, 965 (1938); *Ceram. Abs.*, **18** [5] 129 (1939).

47. A. T. GREEN, W. HUGILL, AND H. ELLERTON, "Blast-Furnace Linings: III, Preliminary Results of Examination of Brick Taken from Furnaces Off for Relining," *Iron & Steel Inst., Special Rept.*, No. 26, pp. 217–32 (1939); *Ceram. Abs.*, **19** [7] 163 (1940).

48. W. WOODHOUSE, W. HUGILL, AND A. T. GREEN, "Blast-Furnace Linings: IV, Investigation of Linings of Three Blown-Out Furnaces," *Iron & Steel Inst., Special*

Rept., No. 26, pp. 233–94 (1939); *Ceram. Abs.*, **19** [7] 163 (1940).

49. T. L. Hurst, "Slag Action of Alkalis on Refractories," *Amer. Refrac. Inst. Tech. Bull.*, No. 75, 7 pp. (July, 1940); *Ceram. Abs.*, **20** [1] 19 (1941).

50. J. B. Austin and M. J. Day, "Chemical Equilibrium and Control of Furnace Atmospheres, Review of Equilibrium Data," *Ind. Eng. Chem.*, **33** [1] 23–31 (1941); *Ceram. Abs.*, **20** [3] 76 (1941).

51. J. H. Loux, "Effect on Furnace Refractories of Protective Gases for High-Carbon Steels," *Ind. Eng. Chem.*, **33** [1] 42–46 (1941); *Trans. Amer. Soc. Metals*, **28** [4] 877–91 (1940); *Ceram. Abs.*, **20** [3] 70; [6] 145 (1941).

(3) Alkali Action on Refractories

52. F. H. Clews, A. Green, and A. T. Green, "Action of Alkalis on Refractory Materials: I, Action of Potash Vapor on Refractory Materials at 900° and 1000°C.," *Bull. Brit. Refrac. Research Assn.*, No. 32 (Oct., 1933); reprinted in *Trans. Ceram. Soc.*, [England], **34** [10] 436–55 (1935); *Ceram. Abs.*, **15** [7] 207 (1936).

53. F. H. Clews and A. T. Green, "Action of Alkalis on Refractory Materials: Summary of Parts I–IX," *Iron & Steel Inst., Special Rept.*, No. 26, pp. 359–83 (1939).

54. F. H. Clews, H. M. Richardson, and A. T. Green, "Action of Alkalis on Refractory Materials: X, Examinations of Reactions of NaCl Vapor with Refractory Materials at 1000°C., and Conditions Leading to Volatilization of Brick Constituents; XI, Experiments on Alterations in Strength When Refractory Materials Are Exposed to KCl Vapor at 1000°C.," *Iron & Steel Inst., Special Rept.*, No. 26, pp. 385–400 (1939); *Refrac. Materials Joint Comm., 29th Rept., Inst. Gas Engrs. Commun.*, No. 193, pp. 9–20 (Nov., 1938); *Ceram. Abs.*, **18** [8] 211 (1939).

(4) Abrasion of Refractories

55. C. E. Nesbitt and M. L. Bell, "Practical Methods for Testing Refractory Firebrick, Hot and Cold Abrasion Tests," *Chem. & Met. Eng.*, **15**, 210 (1916); *Proc. Amer. Soc. Testing Materials*, **16**, 350–72 (1916); p. 368.

56. L. Bradshaw and W. Emery, "Some Comparative Tests of Machine-Made and Hand-Made Silica Brick," *Pottery Gaz.*, **501**, 1338–39 (1919); *Trans. Ceram. Soc.*, [England], **19**, 73–83 (1920); p. 79; *Jour. Amer. Ceram. Soc. (Abstract Section)*, **3** [1] 80 (1920).

57. M. L. Hartmann and O. A. Hougen, "Physical Characteristics of Refractories: I, Spalling Losses; II, Cold and Hot Abrasion Tests," *Trans. Amer. Electrochem. Soc.*, **36** [preprint] (1920); *Jour. Amer. Ceram. Soc. (Abstract Section)*, **4** [3] 239 (1921).

58. W. C. Hancock and W. E. King, "Note on Abrasion of Fire-Clay Materials," *Trans. Ceram. Soc.* [England], **22**, 317–22 (1923); *Ceram. Abs.*, **3** [10] 291 (1924).

59. J. B. Shaw, G. J. Bair, and M. C. Shaw, "Progress Report on Development of Abrasion Test for Refractories at High Temperatures," *Jour. Amer. Ceram. Soc.*, **13** [7] 427–36 (1930).

(5) Miscellaneous on Blast-Furnace Refractories

60. Peters, The Blast Furnace, Chapt. 7, p. 115. McGraw-Hill Book Co., Inc., New York, N. Y., 1907.

61. R. M. Howe, "Blast-Furnace Refractories," *Bull. Amer. Inst. Mining Met. Engrs.*, p. 1791–1802 (1919).

62. J. S. Unger, discussion on "Blast-Furnace Refractories" by R. M. Howe, *Mining & Met.*, pp. 3049–50 (1919).

63. A. P., "Carbon Brick," *Ziegelwelt* (formerly *Deut. Töpfer Ziegler Ztg.*), **53**, 219–20 (1922); *Ceram. Abs.*, **2** [1–2] 17 (1923).

64. P. O. Menke, "Blast-Furnace Lining Failures Caused by Zinc," *Iron Trade Rev.*, **70**, 1409–10 (1922); *Ceram. Abs.*, **1** [10] 253 (1922).

65. F. Clements, "Modern British Blast Furnaces," *Iron & Coal Trades Rev.*, **108** [January–June] 959–64, 1024 (1924); *Ceram. Abs.*, **3** [10] 290 (1924).

66. H. O. Hoffman and C. R. Hayward, Metallurgy of Copper. Chapter on "Smelting in Blast Furnace," p. 109. McGraw-Hill Book Co., Inc., New York, N. Y., 1924.

67. M. C. Booze, "Refractories for Blast Furnaces and Coke Ovens," *Blast Furnace & Steel Plant*, **14** [2] 86–88 (1926); *Ceram. Abs.*, **5** [4] 124 (1926).

68. S. P. Kinney and E. W. Guernsey, "Occurrence, Distribution, and Significance of Alkali Cyanides in the Iron-Blast Furnace," *U. S. Bur. Mines Tech. Paper*, No. 390, 37 pp. (1926); *Ceram. Abs.*, **6** [6] 225 (1927).

69. F. H. Clews and A. T. Green, "Permeability of Refractory Materials to Gases," *Amer. Refrac. Inst. Tech. Bull.*, No. 49 (April 1934); abstracted from series of articles published in *Trans. Ceram. Soc.* [England], **32**, 295–331 (1933); **33**, 21–32 (1934).

70. C. L. Beattie, "Failure of Blast-Furnace Linings," *Iron & Coal Trades Rev.*, **124** [3337] 273–74 (1932); *Ceram. Abs.*, **12** [2] 65 (1933).

71. A. B. Searle, "Refractory Materials for Blast Furnaces, I–III," *Blast Furnace & Steel Plant*, **22** [9] 540–41; [10] 600–601; [11] 660–61 (1934); *Metallurgia*, **9** [51] 85–87 (1934); *Ceram. Abs.*, **13** [7] 183 (1934).

72. V. M. Streletz, "Cracks in Blast-Furnace Refractories," *Ogneupory*, **2** [12] 17–28 (1934); *Ceram. Abs.*, **14** [8] 189 (1935).

73. H. D. Tyson, "Brick Mason and Blast Furnace, II," *Blast Furnace & Steel Plant*, **23** [7] 472–74 (1935); *Ceram. Abs.*, **14** [10] 248 (1935).

74. R. H. Sweetser, Blast-Furnace Practice. McGraw-Hill Book Co., Inc., New York, N. Y., 1938.

75. W. R. McLain, "Blast-Furnace Refractories: Present Application and Possible Future Development," *Bull. Amer. Ceram. Soc.*, **19** [2] 62–68 (1940).

Acknowledgment

The author acknowledges the valued assistance of M. A. Fay and J. Deegan in gathering and preparing samples, W. E. Steiner for personal attention in the analytical work, and D. M. Fraser for petrographic analyses.

Development and Research Department
Bethlehem Steel Company
Bethlehem, Pennsylvania

INFLUENCE OF FLUXES OF SPODUMENE AND FELDSPAR MIXTURES ON PROPERTIES OF CHINAWARE BODIES*

By H. G. Schurecht, J. K. Shapiro, and Z. Zabawsky

Abstract

The most fusible spodumene-feldspar mixture used in these studies was composed of 30% of spodumene, 10% of potash feldspar, and 60% of soda feldspar. In semi-vitreous bodies and vitreous hotel chinaware bodies, however, the most effective fluxes were made up of 30 to 40% of spodumene, 40 to 60% of potash feldspar, and 10 to 20% of soda feldspar. Such fluxes lowered the maturing temperature of these bodies and improved their strength at lower temperatures. When they were fired at cones 6 to 9, their resistance to impact was equal to or higher than that of the feldspar bodies.

I. Introduction

Boyd[1] has shown that although spodumene ($Li_2O \cdot Al_2O_3 \cdot 4SiO_2$) has a higher softening point than feldspar, certain mixtures of spodumene and feldspar may have a softening point nine cones lower than that of feldspar. New methods of concentrating this mineral have made it available for ceramic uses. When it is heated to lime-kiln temperatures, it expands and is converted into a chalky white mass which may be removed from the other minerals by air separation.[2] A method of concentrating it by flotation has also been developed.[3]

Chemical analyses of spodumene and feldspars*

	Spodumene (%)	Potash feldspar (%)	Soda feldspar (%)
SiO_2	64.42	66.04	69.90
Al_2O_3	27.71	19.25	18.41
Fe_2O_3	0.49	0.07	0.09
CaO	.10	0.28	1.10
K_2O	.34	12.10	3.90
Na_2O	0.47	1.82	6.42
Li_2O	5.98		
Loss	0.46	0.43	0.28

* The spodumene and feldspars were furnished by the United Feldspar and Minerals Corp., New York, N. Y.

By using certain spodumene-feldspar mixtures as fluxes in whiteware bodies to replace feldspar, many of the properties of the bodies were improved. The mixture which produced the greatest fluxing action, however, varied for different bodies and firing temperatures and did not always correspond to the most fusible mixture of spodumene, potash feldspar, and soda feldspar.

II. Materials and Experimental Methods

(1) Spodumene-Feldspar Mixtures

The spodumene used in this investigation was separated by flotation. The chemical analyses of these mixtures are given in the opposite column.

Although the soda feldspar is not a true soda feldspar because it contains 3.90% potash, it will be referred to in this report as soda feldspar to differentiate it from the potash feldspar.

The compositions of the mixtures are given in Table I.

Table I

Compositions of Spodumene-Feldspar Mixtures

No.	Composition (%) Spodumene	Potash feldspar	Soda feldspar	No.	Composition (%) Spodumene	Potash feldspar	Soda feldspar
1	00	100	00	34	30	40	30
2	"	90	10	35	"	30	40
3	"	80	20	36	"	20	50
4	"	70	30	37	"	10	60
5	"	60	40	38	"	0	70
6	"	50	50	39	40	60	0
7	"	40	60	40	"	50	10
8	"	30	70	41	"	40	20
9	"	20	80	42	"	30	30
10	"	10	90	43	"	20	40
11	"	00	100	44	"	10	50
12	10	90	00	45	"	00	60
13	"	80	10	46	50	50	00
14	"	70	20	47	"	40	10
15	"	60	30	48	"	30	20
16	"	50	40	49	"	20	30
17	"	40	50	50	"	10	40
18	"	30	60	51	"	00	50
19	"	20	70	52	60	40	00
20	"	10	80	53	"	30	10
21	"	00	90	54	"	20	20
22	20	80	00	55	"	10	30
23	"	70	10	56	"	00	40
24	"	60	20	57	70	30	00
25	"	50	30	58	"	20	10
26	"	40	40	59	"	10	20
27	"	30	50	60	"	00	30
28	"	20	60	61	80	20	00
29	"	10	70	62	"	10	20
30	"	00	80	63	"	00	20
31	30	70	00	64	90	10	00
32	"	60	10	65	"	00	10
33	"	50	20	66	100	00	00

* Presented at the Forty-Third Annual Meeting, The American Ceramic Society, Baltimore, Md., April 3, 1941 (White Wares Division). Received December 4, 1941.

[1] J. E. Boyd, "Pyrometric Properties of Spodumene-Feldspar Mixtures," *Jour. Amer. Ceram Soc.*, 21 [11] 385–88 (1938).

[2] Foster Fraas and O. C. Ralston, "Beneficiation of Spodumene by Decrepitation," *U. S. Bur. Mines Repts. Investigations*, No. 3336, 13 pp. (1937); *Ceram. Abs.*, 17 [4] 158 (1938).

[3] James Norman and E. W. Gieseke, "Beneficiation of Spodumene by Froth Flotation," *Amer. Inst. Mining Met. Engrs. Tech. Pub.*, No. 1161 (1939); *Mining Tech.*, 4 [2] 9 pp. (1940); *Ceram. Abs.*, 19 [8] 198 (1940).

(2) Semivitreous Bodies

The semivitreous bodies were composed of Great Beam English ball clay 13.5%, EPK Florida kaolin 7.5%, MGR-1 English china clay 34.0%, flint 35%, and spodumene-feldspar mixtures 10.0%. The compositions of the spodumene-feldspar mixtures for these bodies are given in Table III.

The porosity and volume shrinkage of these bodies were determined after firing to cones 6, 8, and 12.

(3) Vitreous Hotel Chinaware

The vitreous body was composed of Great Beam English ball clay 8.0%, EPK Florida kaolin 6.0%, MGR-1 English china clay, 33.0%, flint 34.5%, whiting 2.5%, and spodumene-feldspar mixtures 16%. The compositions of the spodumene-feldspar mixtures for hotel chinaware bodies are given in Table III.

The bodies were prepared by blunging, screening, and filter pressing, and their porosity, shrinkage, and strength values were measured after firing to cones 6, 8, and 12 in 36 hr. in a gas-fired laboratory kiln. An average of 16 bars was used in calculating the moduli of rupture of the bodies.

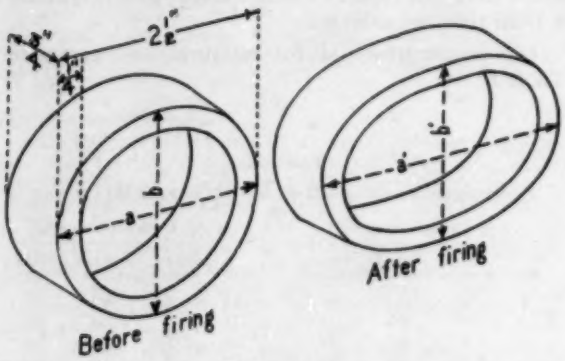

FIG. 1.—Method of measuring warpage by means of slump of rings.

The warpage was determined by noting the slump of ring-shaped specimens (see Fig. 1). This test has been used at some of the whiteware plants as a measure of warpage. The ratio of horizontal to vertical diameters is determined before and after firing, and the warpage factor is calculated by equation (1).

$$W = \frac{a'}{b'} - \frac{a}{b}. \qquad (1)$$

W = warpage factor.
a' = horizontal outside diameter after firing.
b' = vertical " " " "
a = horizontal outside diameter before firing.
b = vertical " " " "

The specimen disks used for the impact tests were $2^1/_2$ in. in diameter and $^1/_4$ in. thick, and a 4-ounce hammer was used as specified in Federal Specification M–C-301 for Vitrified Chinaware. The unglazed disks were supported against three $^1/_8$-in. balls, equally spaced, so that when the hammer was hanging vertically its impact point touched the center of the test piece. Because the disks were not glazed, they were not so resistant to impact as glazed ware. An initial blow of 0.02 ft.-lb. was therefore used in place of 0.10 ft.-lb., inasmuch as the latter blow broke the specimens too easily. They were struck with blows of increasing increments of 0.02 ft.-lb. until failure occurred. Cracks on the side opposite that struck by the hammer which did not extend through the piece were designated

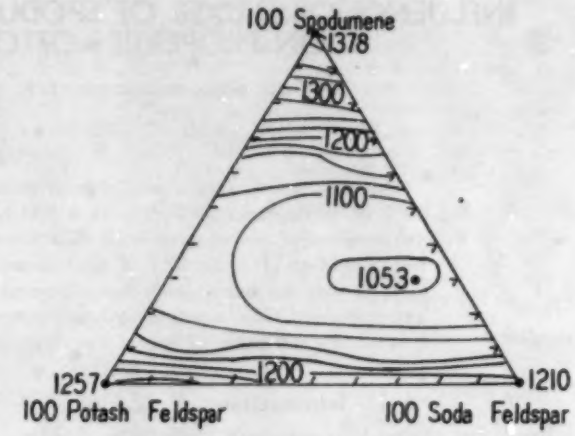

FIG. 2.—Softening temperatures of spodumene and potash and soda feldspar mixtures.

TABLE II

P.C.E. VALUES AND SOFTENING TEMPERATURES OF SPODUMENE AND POTASH AND SODA FELDSPAR MIXTURES

Mix No.	P.C.E.	Temp. °C.	Mix No.	P.C.E.	Temp. °C.
1	10^4	1257	34	02^1	1082
2	10^6	1260	35	03^4	1071
3	9^4	1242	36	03^4	1071
4	9^2	1233	37	03^1	1053
5	8^6	1225	38	02^1	1082
6	8^3	1218	39	1^2	1115
7	8^2	1215	40	01^3	1100
8	8^2	1215	41	02^6	1095
9	7^6	1210	42	03^6	1080
10	7^6	1210	43	02^2	1085
11	7^6	1210	44	03^6	1080
12	5^9	1177	45	02^6	1095
13	4^2	1151	46	1^4	1121
14	4^3	1151	47	1^3	1115
15	4^4	1169	48	01^6	1110
16	4^1	1147	49	01^1	1097
17	3^3	1140	50	02^6	1095
18	3^1	1136	51	02^6	1095
19	1^3	1115	52	2^5	1132
20	3^1	1136	53	3^2	1138
21	2^5	1132	54	2^5	1132
22	2^3	1130	55	5^2	1170
23	01^6	1110	56	5^6	1180
24	01^5	1103	57	9^1	1228
25	01^1	1097	58	9^1	1228
26	02^2	1085	59	9^2	1233
27	02^3	1085	60	8^6	1225
28	02^3	1085	61	11^2	1273
29	02^1	1082	62	11^6	1285
30	02^1	1082	63	12^5	1305
31	1^2	1115	64	13^5	1342
32	2^2	1128	65	14^2	1362
33	01^1	1097	66	14^4	1378

TABLE III

EFFECT OF MIXTURES OF SPODUMENE AND POTASH AND SODA FELDSPARS ON POROSITY AND SHRINKAGE OF SEMIVITREOUS DINNERWARE AND VITREOUS HOTEL CHINAWARE BODIES

Body	Spodumene-feldspar mixtures (%)			Porosity (%) at			Volume shrinkage (%) at		
	Spodumene	Potash feldspar	Soda feldspar	Cone 6	Cone 8	Cone 12	Cone 6	Cone 8	Cone 12
				Semivitreous dinnerware bodies					
A	7	2	1	18.4	16.1	8.4	19.9	21.1	25.1
B	7		3	20.7	19.0	10.3	17.6	19.7	24.6
C	6	4		17.4	15.2	5.8	21.4	21.4	26.8
D	6	2	2	17.4	15.7	6.8	20.8	21.7	25.3
E	6		4	20.0	17.9	8.5	16.5	19.3	24.3
F	5	4	1	17.8	14.3	5.3	20.2	22.1	26.7
G	5	2	3	18.0	14.7	7.1	20.4	21.9	25.8
H	5		5	19.3	16.7	9.3	19.5	20.1	24.7
I	4	6	0	17.1	14.2	3.0	19.8	22.5	28.2
J	4	4	2	14.9	15.4	4.9	18.7	22.0	27.3
K	4	2	4	18.8	14.4	6.9	19.4	21.4	26.8
L	4	0	6	18.8	17.8	8.8	20.0	20.3	24.8
M	3	6	1	20.3	14.0	3.8	19.0	22.8	28.6
N	3	4	3	18.7	15.4	4.3	20.6	22.5	28.3
O	3	2	5	16.8	14.6	6.4	21.4	21.6	26.4
P	3		7	19.2	16.3	9.7	19.0	20.8	24.6
Q	2	6	2	18.9	14.4	4.3	17.8	22.6	29.3
R	2	4	4	17.9	17.1	5.1	20.2	19.7	28.1
S	2	2	6	19.7	14.3	6.2	18.6	21.6	26.4
T	2		8	19.4	18.3	8.8	18.6	20.3	24.5
U	1	6	3	22.7	15.5	3.7	24.5	21.8	29.4
V	1	4	5	17.4	16.1	3.5	20.0	20.9	28.2
W	1	2	7	20.4	18.8	5.5	18.4	19.8	27.3
Y		6	4	25.9	20.2	4.5	17.2	18.1	28.6
Z		4	6	22.8	18.5	5.3	15.6	18.5	28.3
AA		2	8	23.7	19.5	6.1	14.7	17.0	27.3
				Vitreous hotel chinaware bodies					
A	11.2	3.2	1.6	5.3	2.7	0.4	25.5	30.7	23.3
B	11.2		4.8	14.7	2.8	0.3	23.2	27.1	26.4
C	9.6	6.4		3.4	1.9	0.1	30.1	30.3	26.2
D	9.6	3.2	3.2	5.8	2.3	0.6	26.2	29.4	24.8
E	9.6		6.4	7.7	3.1	1.1	15.0	28.2	25.4
F	8.0	6.4	1.6	5.3	2.2	0.0	27.7	29.7	20.7
G	8.0	3.2	4.8	8.9	2.4	0.2	28.9	30.9	22.5
H	8.0		8.0	4.7	1.9	0.0	23.9	28.8	26.4
I	6.4	9.6		5.8	1.6	0.0	29.2	30.4	23.5
J	6.4	6.4	3.2	5.2	1.6	0.5	27.5	30.2	25.8
K	6.4	3.2	6.4	8.7	3.4	0.4	27.4	30.0	24.9
L	6.4		9.6	6.5	2.2	0.0	25.0	28.8	27.0
M	4.8	9.6	1.6	5.5	2.4	0.0	27.8	30.5	28.1
N	4.8	6.4	4.8	8.3	3.1	0.2	27.3	29.9	29.0
O	4.8	3.2	8.0	7.4	3.6	0.6	26.7	29.6	26.8
P	4.8		11.2	7.3	3.1	0.0	25.0	28.6	27.5
Q	3.2	9.6	3.2	7.7	3.3	0.0	26.1	29.8	26.4
R	3.2	6.4	6.4	15.3	4.1	0.0	26.3	29.8	28.5
S	3.2	3.2	9.6	14.0	5.7	0.0	22.5	29.3	29.6
T	3.2		12.8	15.6	6.1	0.0	25.9	27.8	30.2
U	1.6	9.6	4.8	12.0	4.9	0.0	23.2	27.4	31.2
V	1.6	6.4	8.0	15.1	5.7	0.0	24.1	28.3	30.9
W	1.6	3.2	11.2	17.2	8.0	0.0	21.9	26.4	29.4
X		16.0		12.3			19.0		
Y		9.6	6.4	17.4	9.0	0.0	21.0	26.8	31.0
Z		6.4	9.6	20.8	10.3	0.0	19.6	25.2	31.1
AA		3.2	12.8				19.1	25.0	27.6

as "starring" and those which extended through the specimens were called "fractures." After each blow, they were examined for cracks, and ink was applied to mark the cracks.

III. Results

The results of fusion tests of spodumene-feldspar mixtures are shown in Table II and Fig. 2.

Table III shows the effect of the spodumene-feldspar mixtures on the porosity and shrinkage of semivitreous bodies, and the porosities of these at cones 6 and 8 have been plotted in Figs. 3 and 4. Table III also shows the influence of these fluxes on the porosity and shrinkage of vitreous chinaware bodies, and the porosities at cones 6 and 8 have been plotted in Fig. 5.

The strength, warpage, and impact resistance of the more promising bodies are shown in Table IV, and the strength tests have been plotted in Fig. 6.

TABLE IV

EFFECT OF MIXTURES OF SPODUMENE AND POTASH AND SODA FELDSPARS ON STRENGTH, WARPAGE, AND IMPACT RESISTANCE OF VITREOUS HOTEL CHINAWARE BODIES

	Modulus of rupture (lb./in.²)				Warpage factor (Increase in ratio of horizontal to vertical diameter)				
Body	Cone 7	Cone 8	Cone 9	Cone 11[3]	Cone 8	Cone 9[3]	Cone 10	Cone 11[3]	Cone 13[3]
X	2940	3394	3734	5023	0.008	0.017	0.015	0.021	0.026
C	4262	4733	6340	6232	.026	.025	.024		.083
G		4490	6241	6337	.024	.025	.031	.026	.059
I	3960	4777	5785	7114	.030	.024	.036	.026	.082
J	3760	4899	5287	5815	.024	.027	.018	.018	.054
K		4168	5444	6209	.027	.032	.036	.031	.066

	Impact force (ft.-lb.)				
	0.02	0.04	0.06	0.08	0.10
			Cone 8		
X	O.K.	O.K.	1 fracture	3 fractures	
C	"	"	1 "	3 "	
G	"	"	O.K.	1 "	2 fractures
I	"	"	Starring	2 "	
J	"	Starring	1 fracture		
K	"	O.K.	Starring	2 "	
			Cone 9		
X	"	Starring	Starring	2 "	
C	"	O.K.	3 fractures		
G	"	"	O.K.	1 "	
I	"	"	2 fractures	Starring	
J	"	"	O.K.	2 fractures	3 "
K	"	"	Starring	1 "	
			Cone 13[3]		
X	"	"	O.K.	3 "	
C	"	"	3 fractures		
I	"	"	1 "	3 "	
J	"	"	1 "	2 "	3 "
K	"	"	O.K.	O.K.	3 "

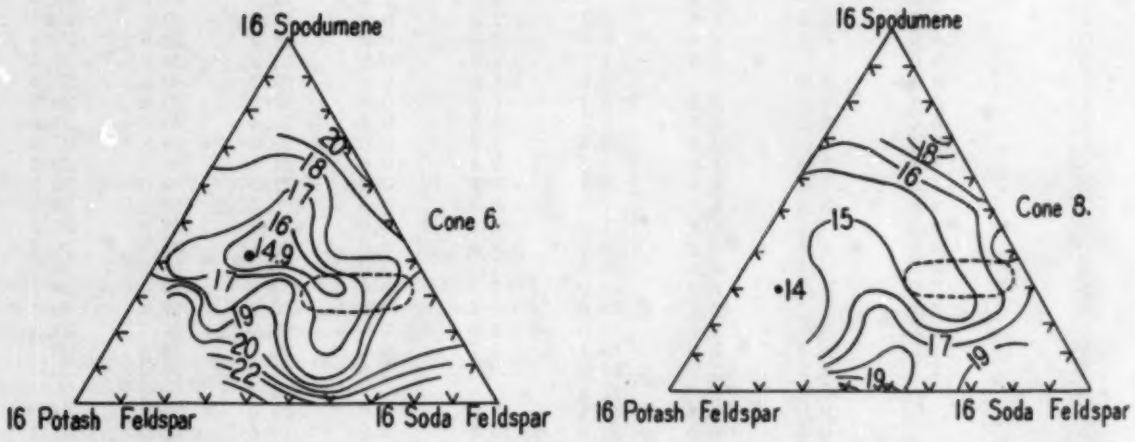

FIG. 3.—Porosity of semivitreous bodies with fluxes composed of spodumene and potash and soda feldspar mixtures at cones 6 and 8.

IV. Discussion of Results

(1) Spodumene-Feldspar Mixtures

The lowest fusing mixture was composed of 30% of spodumene, 10% of potash feldspar, and 60% of soda feldspar (Fig. 2). It softened at 1053°C., which is 325° lower than that of potash feldspar and 157° lower than that of the soda feldspar.

(2) Semivitreous Ware

At cone 6, bodies with minimum porosity were produced with 40% of spodumene, 40% of potash feldspar, and 20% of soda feldspar (Figs. 3 and 4); at cone 8, minimum porosity was produced with 30% of spodumene, 60% of potash feldspar, and 10% of soda feldspar; and at cone 12, minimum porosity was obtained with 40% of spodumene and 60% of potash feldspar.

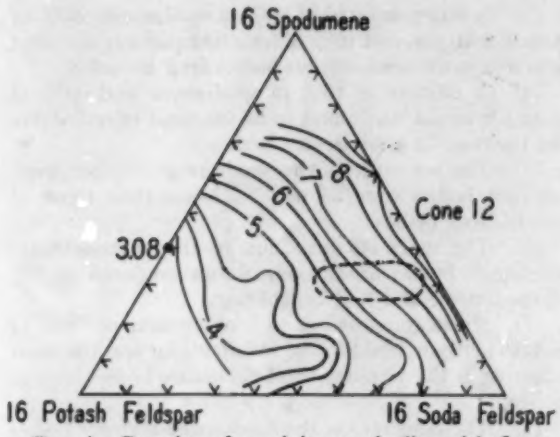

FIG. 4.—Porosity of semivitreous bodies with fluxes composed of spodumene and potash and soda feldspar mixtures.

The most fusible mixture of the spodumene and feldspars apparently did not produce maximum vitrification when these were used as fluxes in semivitreous bodies. The most effective mixtures in the bodies varied considerably depending on the temperature to which they were fired. The areas representing the most fusible spodumene-feldspar mixtures have been circumscribed with dotted lines in Figs. 2 to 5 for comparison with the most vitreous bodies produced by these fluxes.

At cone 6, the porosity of the spodumene-feldspar bodies was decreased about 35% as compared with feldspar bodies; at cone 8, it was lowered about 30%; and at cone 12, it was decreased 65%.

The shrinkage data indicate that these bodies in general were not overfired and that the most vitreous bodies also developed the greatest shrinkage as was expected.

(3) Vitreous Hotel Chinaware

Bodies with minimum porosity were produced at cone 6 with 60% of spodumene and 40% of potash feldspar (see Fig. 5). At cone 8, minimum porosity was produced with 40% of spodumene, 40% of potash feldspar, and 20% of soda feldspar. Because many of the bodies were overfired at cone 12, it was difficult to select those with minimum absorption. It is evident, however, that the most fusible mixtures of spodumene and the feldspars did not produce maximum vitrification when these were used as fluxes in vitreous as well as semivitreous bodies. The most effective mixture varied considerably depending on the temperature at which the ware was fired.

At cones 6 and 8, the porosity was decreased about 80% by using spodumene-feldspar mixtures in place of feldspar.

Spodumene-feldspar mixtures produced much stronger bodies than those obtained with potash feldspar alone (Fig. 6). Body C, which contained a flux composed of 60% of spodumene and 40% of potash feldspar, and body G, which contained 50% of spodumene, 20% of potash feldspar, and 30% of soda feld-

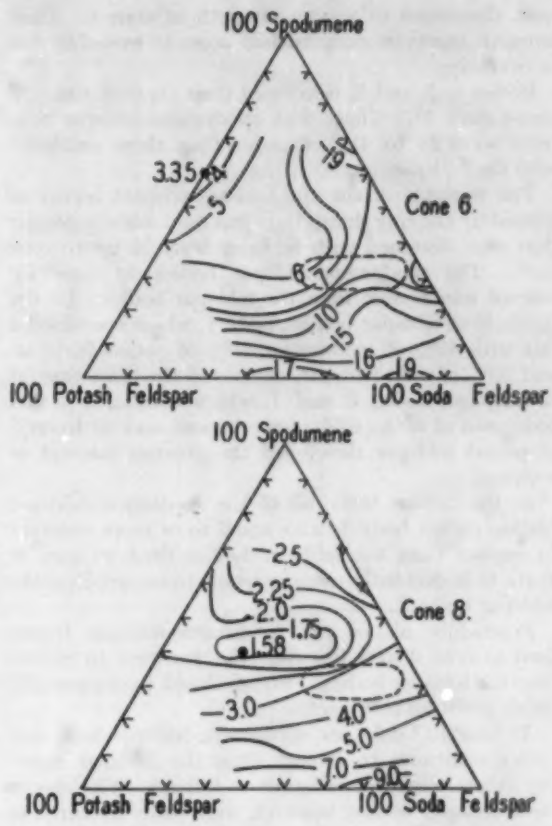

FIG. 5.—Porosity of vitreous hotel chinaware bodies with fluxes composed of spodumene and potash and soda feldspar mixtures at cones 6 and 8.

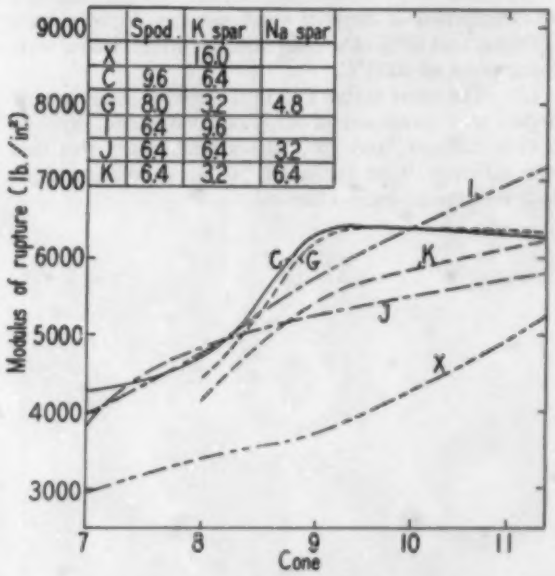

FIG. 6.—Strength of vitreous chinaware bodies with fluxes composed of spodumene and potash and soda feldspar mixtures.

spar, developed maximum strength at cone 9. Their strength however, decreased at cone 11 probably due to overfiring.

Bodies I, J, and K developed their greatest strength above cone 11. Those with spodumene-feldspar mixtures were 14 to 41% stronger than those produced with the feldspars alone.

The warpage of the spodumene-feldspars bodies as judged by the ring slump tests was only slightly greater that that obtained with feldspar body X up to cone 11.[3] The spodumene-feldspar bodies at cone 13[3] warped much more than the feldspar bodies. Of the spodumene-feldspar bodies, body J, which contained a flux with 40% of spodumene, 40% of potash feldspar, and 20% of soda feldspar, developed the least amount of warpage; bodies C and I, which contained a flux composed of 60 to 40% of spodumene and 40 to 60% of potash feldspar, developed the greatest amount of warpage.

In the impact tests, all of the spodumene-feldspar bodies, except body J, were equal to or more resistant to impact than the feldspar bodies fired to cone 8. Body G is decidedly more resistant to impact than the feldspar body X.

Practically all of the spodumene-feldspar bodies fired to cone 9 were likewise more resistant to impact than the feldspar bodies. Bodies G and J are especially highly resistant to impact.

At cone 13,[3] only one spodumene-feldspar body had better resistance to impact than the feldspar body; the others were less resistant to impact. The spodumene-feldspar bodies, however, were badly overfired at this temperature, which evidently accounts for their poorer resistance to impact.

V. Summary

(1) The most fusible spodumene-feldspar mixture was composed of 30% of spodumene, 10% of potash feldspar, and 60% of a soda feldspar which had a softening point of 1053°C.

(2) The most active flux in the cone 6 semivitreous bodies was composed of 40% of spodumene, 40% of potash feldspar, and 20% of soda feldspar; this flux was different from the most fusible spodumene-feldspar mixture given in (1).

(3) A flux composed of 30% of spodumene, 60% of potash feldspar, and 10% of soda feldspar was the most effective in the semivitreous bodies fired at cone 8.

(4) A mixture of 40% of spodumene and 60% of potash feldspar was found to be the most effective flux for the cone 12 semivitreous bodies.

(5) The porosities of the spodumene-feldspar semivitreous bodies were 35 to 65% lower than those of the feldspar bodies.

(6) The most effective flux in the vitreous hotel chinaware bodies fired to cone 6 was composed of 60% of spodumene and 40% of feldspar.

(7) A flux composed of 40% of spodumene, 40% of potash feldspar, and 20% of soda feldspar was the most effective in the vitreous hotel chinaware bodies fired to cone 8.

(8) The porosities of the spodumene-feldspar bodies were 80% lower in some cases than those of the feldspar bodies fired to the same temperature.

(9) Spodumene-feldspar vitreous china bodies were (approximately) 14 to 41% stronger in some cases than feldspar bodies fired to the same temperature.

(10) The warpage of the spodumene-feldspar bodies was only slightly greater than that obtained with the feldspar bodies at temperatures below cone 11. At cone 13, however, the spodumene-feldspar bodies warped much more than the feldspar bodies.

(11) The spodumene-feldspar vitreous hotel chinaware bodies, fired at cones 6 to 9, were equally or more resistant to impact than the feldspar body. When fired to cone 13, however, these bodies were overfired and had poorer resistance to impact.

(12) The main advantages, therefore, to be gained by the use of spodumene-feldspar mixtures to replace feldspar in whiteware bodies is a lowering of the vitrification temperature and an improvement in the strength of the bodies fired to the lower temperatures.

Acknowledgment

The writers wish to acknowledge their indebtedness to the United Feldspar and Minerals Corporation for their cooperation in this work and also to M. E. Holmes for helpful suggestions during the progress of the work.

Ceramic Experiment Station
New York State College of Ceramics
Alfred, New York

OFFICIAL PERSONNEL OF DIVISIONS, 1942–1943

	Art	Enamel	Glass	Materials and Equipment	Refractories	Structural Clay Products	White Wares
Trustee	L. E. Barringer	J. E. Hansen	G. W. Morey	J. E. Eagle	J. D. Sullivan	Frederick Heath, Jr.	F. P. Hall
Chairman	J. A. Foster	Karl Kautz	W. C. Taylor	J. F. McMahon	R. S. Bradley	R. A. Shipley	F. C. Henderson
Vice-Chairman	A. E. Baggs	D. G. Bennett	J. F. Greene	E. M. Rupp	C. L. Thompson	R. L. Stone	
2d Vice-Chairman	H. S. Nash		C. W. Parmelee				
Secretary	Marion L. Fosdick	D. G. Moore	S. R. Scholes	J. R. Kauffman	W. R. Kerr	E. F. Theobald	J. R. Beam
Division Nominations	A. A. Ayers	W. G. Martin R. J. Whitesell W. W. Higgins	F. C. Flint J. C. Hostetter E. W. Tillotson	B. T. Bonnot S. S. Cole	Gilbert Solér C. A. Freeman		J. W. Whittemore H. Lattimer C. M. Lambe, Jr.
Papers and Program	H. S. Nash	D. G. Bennett	J. F. Greene	A. B. Scholes E. W. Koenig N. B. Davis B. S. Ellefson	S. M. Swain P. G. Herold C. L. Norton E. E. Callinan	R. L. Stone J. H. Isenhour V. W. Boeker	C. J. Koenig
Membership	Carlton Atherton	O. E. Mulvane	W. R. Lester	H. B. Foster, Jr.	E. C. Petrie	L. R. Whitaker	W. E. Welliver
Standards	F. R. Matson	R. L. Cook	A. E. Badger F. W. Adams H. P. Hood		E. E. Callinan	Frederick Heath, Jr.	F. P. Hall
Research	H. E. Marley	M. J. Bahnsen	J. S. Gregorius H. R. Lillie A. Silverman		D. W. Ross	J. G. Seanor	Ralston Russell, Jr.
Data	M. L. Fosdick	H. L. Cook			Grant Diamond	Ernest Merry, Jr.	R. M. Campbell
Rules	Theodore Lenchner	E. E. Howe	D. E. Sharp	W. R. Malkin	S. P. Walton	Frederick Heath, Jr. J. W. Whittemore D. F. Stevens	W. E. Palmer
Councillors	A. E. Baggs C. M. Harder	J. D. Tetrick R. L. Fellows	A. K. Lyle U. E. Bowes	V. V. Kelsey		J. L. Child J. W. Whittemore	Ralston Russell, Jr. Edward Schramm
Exhibitions	W. A. Weldon		J. E. Frazier				
Industrial Management	F. H. Rhead		L. C. Roche		O. L. Jones		
Bibliography		J. E. Rosenberg					Harry Thiemecke F. P. Hall P. D. Helser

THE AMERICAN CERAMIC SOCIETY TRUSTEES AND OFFICERS FOR 1942–1943

President: Louis J. Trostel, General Refractories Co., Baltimore, Md.
Vice-President: M. E. Holmes, N. Y. State College of Ceramics, Alfred, N. Y.
Treasurer: C. Forrest Tefft, The Claycraft Co., Columbus, Ohio
Secretary-Editor: R. C. Purdy, 2525 North High St., Columbus, Ohio
Past-President: J. T. Littleton, Corning Glass Works, Corning, N. Y.
Past-President: J. L. Carruthers, Ohio State University, Columbus, Ohio

TRUSTEES FROM INDUSTRIAL DIVISIONS*

Art: L. E. Barringer, General Electric Co., Schenectady, N. Y. (1943)
Enamel: J. E. Hansen, Ferro Enamel Corp., Cleveland, Ohio (1943)
Glass: G. W. Morey, Geophysical Laboratory, Washington, D. C. (1944)
Materials and Equipment: J. E. Eagle, Vitro Mfg. Co., Pittsburgh, Pa. (1945)
Refractories: J. D. Sullivan, Battelle Memorial Institute, Columbus, Ohio (1943)
Structural Clay Products: Frederick Heath, Jr., Colonial Clays, Inc., Worcester, Mass. (1945)
White Wares: F. P. Hall, Onondaga Pottery Co., Syracuse, N. Y. (1944)
Institute of Ceramic Engineers: H. G. Wolfram, Porcelain Enamel & Mfg. Co., Baltimore, Md. (1944)
Ceramic Educational Council: J. W. Whittemore, Virginia Polytechnic Institute, Blacksburg, Va. (1944)

* Date of expiration of term of office in parentheses.

DIVISION OFFICERS

Art
Chairman: J. A. Foster, 9591 Sorrento Ave., Detroit, Mich.
Secretary: Marion L. Fosdick, N. Y. State College of Ceramics, Alfred, N. Y.

Enamel
Chairman: Karl Kautz, Climax Molybdenum Co., First National Bank Bldg., Canton, Ohio
Secretary: D. G. Moore, National Bureau of Standards, Washington, D. C.

Glass
Chairman: W. C. Taylor, Corning Glass Works, Corning, N. Y.
Secretary: S. R. Scholes, N. Y. State College of Ceramics, Alfred, N. Y.

Materials and Equipment
Chairman: J. F. McMahon, N. Y. State College of Ceramics, Alfred, N. Y.
Secretary: J. R. Kauffman, Allied Engineering Co., 29 Highland Drive, Milltown, N. J.

Refractories
Chairman: R. S. Bradley, A. P. Green Fire Brick Co., Mexico, Mo.
Secretary: W. R. Kerr, Armstrong Cork Co., Beaver Falls, Pa.

Structural Clay Products
Chairman: R. A. Shipley, National Fireproofing Corp., Pittsburgh, Pa.
Secretary: E. F. Theobald, Metropolitan Paving Brick Co., Canton, Ohio

White Wares
Chairman: F. C. Henderson, Hall China Co., East Liverpool, Ohio
Secretary: J. R. Beam, Universal Sanitary Mfg. Co., New Castle, Pa.

OFFICERS OF THE FELLOWS

Dean: R. B. Sosman, U. S. Steel Corp., Kearny, N. J.
Associate Dean: T. N. McVay, University of Alabama, University, Ala.
Secretary-Treasurer: R. M. King, Ohio State University, Columbus, Ohio

INSTITUTE OF CERAMIC ENGINEERS

President: H. M. Kraner, Bethlehem Steel Co., Bethlehem, Pa.
Vice-President: H. B. DuBois, Consolidated Feldspar Corp., Trenton, N. J.
Secretary: H. G. Schurecht, New York State College of Ceramics, Alfred, N. Y.

CERAMIC EDUCATIONAL COUNCIL

President: N. W. Taylor, Pennsylvania State College, State College, Pa.
Vice-President: R. M. Campbell, N. Y. State College of Ceramics, Alfred, N. Y.
Secretary: C. M. Dodd, Iowa State College, Ames, Iowa

LOCAL SECTIONS

Baltimore-Washington
Chairman: Kenneth M. Smith, Severn Clay Co., Baltimore, Md.
Secretary: W. R. Lester, Maryland Glass Corp., Baltimore, Md.

Central Ohio
Chairman: H. J. Orlowski, O.S.U. Engr. Expt. Sta., Columbus, Ohio
Secretary: A. C. Jackson, The Claycraft Co., Columbus, Ohio

Chicago
Chairman: H. G. Fisk, Armour Research Foundation, Inc., Chicago, Ill.
Secretary: C. R. Filippi, Illinois Brick Co., Chicago, Ill.

Michigan-Northwestern Ohio
Chairman: J. A. Foster, 9591 Sorrento Ave., Detroit, Mich.
Secretary: A. R. Decker, Champion Spark Plug Co., Detroit, Mich.

Northern California
Chairman: G. A. Page, Stockton Fire Brick Co., Pittsburg, Calif.
Secretary: B. W. Wyatt, N. Clark & Sons, Alameda, Calif.

Pacific-Northwest
President: M. D. Saindon, Chehalis Brick & Tile Co., Chehalis, Wash.
Secretary: W. P. Keith, Univ. of Washington, Seattle, Wash.

Pittsburgh
Chairman: G. J. Bair, Mellon Institute, Pittsburgh, Pa.
Secretary: R. M. Shremp, Lava Crucible Co., Zelienople, Pa.

Southern California
Chairman: J. E. Stevens, Emsco Refractories Co., South Gate, Calif.
Secretary: R. F. Evans, Gladding, McBean & Co., Los Angeles, Calif.

St. Louis
Chairman: H. H. Hanna, Pittsburgh Plate Glass Co., Crystal City, Mo.
Secretary: J. H. Ivery, Hydraulic Press Brick Co., St. Louis, Mo.